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Research Projects Laboratory
George C. Marshall Space Flight Center
Huntsville, Alabama

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A STUDY OF LUNAR RESOURCES: A PRELIMINARY REPORT OF SURFACE AND SOME OTHER MINING SYSTEMS

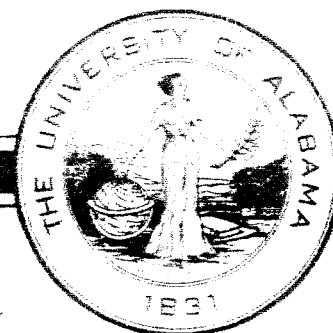
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Request No. DCN 1-5-25-01048-01
May 22, 1965 - May 1, 1966

by

Reynold Q. Shotts, Project Co-Director
Robert M. Cox, Project Co-Director
David M. Grubbs, Research Associate
H. Wm. Ahrenholz, Research Associate



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Summary Report

A STUDY OF LUNAR RESOURCES:
A PRELIMINARY REPORT ON SURFACE
AND SOME OTHER MINING SYSTEMS

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May 22, 1965 - May 1, 1966

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THE CASE FOR DISCOVERY AND UTILIZATION OF LUNAR RESOURCES

Dr. James B. Edson, of the National Aeronautics and Space Administration, in his oral summary of the papers read during the Fourth Annual Meeting of the Working Group on Extraterrestrial Resources, Air Force Academy, Colorado Springs, Colorado, December 1, 1965, remarked that the leading lunar resources likely will prove to be gas wells (C_2H_2) and permafrost. This remark points up the fact that exploitation of extraterrestrial resources for earth use is not contemplated but all plans are directed toward their use in lunar and planetary exploration projects only. His additional remark that the processes for extraction of oxygen from rock is the one to beat further emphasizes the exclusive preoccupation of space exploration planners with problems of life support and fuels in the space program itself.

There are a number of potential advantages in the use of indigenous minerals in connection with the space exploration program over the alternative of transporting everything from the earth. In the last analysis, relative costs probably will decide between the two sources of supply although there are other considerations.

Among the other considerations are:

(1) The safety and flexibility of lunar colonies and expeditions will be greatly enhanced by availability of lunar sources of supply. If return fuel and oxidizer are available on the moon, colonies will no longer be solely dependent upon rigid adherence to a schedule of flights from earth. In case of a lunar plant or supply breakdown, fuel and oxygen can be supplied from the earth and in the case of earth launch failures or delays, the colony will not be endangered. If indigenous fuel materials are not available, a long-term supply from earth may be required for lunar storage, far in excess of anticipated short-term requirements. Lunar sources would eliminate or greatly reduce such a requirement.

(2) The technological requirements for establishment of mining and processing facilities on the moon will not only tax man's ingenuity to the utmost but, just as is true of all the space programs, will produce an abundance of "fallout" for the benefit of both earth technology and the advanced technologies that will be required later for the longer term Mars and other solar system exploration expeditions.

(3) Utilization of lunar resources probably will add greatly to our progress in deciphering the geology and structure of the moon. Just as on earth, we utilize scientific knowledge to explore for minerals and our programs of exploration for and mining of minerals, in turn, add detailed information and correlations to our scientific knowledge. So on the moon, exploration and mining of minerals should add continuously to our fund of detailed knowledge and of over-all understanding of lunar geology and structure begun by Apollo and post-Apollo scientific expeditions (Allenby, 1965).

(4) If recovery of lunar resources can be made economic, this should add to the attractiveness of that body as sites for use as: (a) launching bases for exploration expeditions to the inner solar system, (b) astronomical observatories, (c) earth weather observation stations, and (d) peace-keeping, military observation stations for earth.

Finally, it seems certain that if now or subsequently it is made evident that utilization of indigenous lunar resources can compete economically with the same or similar materials transported from the earth, they will be used. If, however, this cannot be shown, the chances for mining and using these materials, even if demonstratably available, are not good and must await changes in supplies and economic position of earth materials.

II

ECONOMIC LIMITS AND TIME SEQUENCE FOR LUNAR RESOURCE UTILIZATION

The more the problem is studied, the more apparent it becomes that mining and utilizing lunar resources will depend on the comparative economics of mining and processing operations with that of the same materials sent from earth. Even the proved presence of abundant and accessible lunar resources will not guarantee their utilization: an economic technology must still be developed.

Some economic estimates have already been made, based upon assumed specific technologies (Glaser, et al, 1964; Paul, 1965; Rosenberg, et al, 1964). Most have assumed transportation costs of personnel, supplies, equipment, etc., to be \$5000.00 per pound of pay load and the same charge is used for transporting oxygen, hydrogen, or other expected products of lunar mining and processing, from the earth. Lunar labor costs have generally been estimated at \$75,000 to \$100,000 per manhour.

Rosenberg, et al (1964) dealt solely with the Aerojet-General carbothermal process for extracting oxygen from silicates of basic rock mineral composition (MgSiO_3 or Mg_2SiO_4). This process requires the recycling of all hydrogen produced unless the rock contains water in which case the water can be recovered almost quantitatively. In their analysis, Rosenberg, et al, apparently assume that the raw material can be "gathered" at virtually no cost at the plant site as they estimated costs only of silicate reduction, water hydrolysis, oxygen liquefaction, oxygen storage, and of plant delivery, erection, and operation, including power. Estimates were made for 6,000, 12,000, and 24,000 pounds of oxygen per month. It is obvious that if suitable raw material proves difficult to find or must be quarried or mined in some way and transported an appreciable distance to the processing

plant, a substantial increment will be added to the cost of oxygen from the carbo-thermal process.

Glaser, et al (1964) did not make an economic analysis in terms of dollars but they made thermodynamic calculations from which power requirements could be estimated. They studied only in situ water extraction processes for hydrogen production, assuming either permafrost (50% water) or hydrated rock with 1 or 10 percent water.

They were concerned only with hydrogen production, liquefaction and liquid storage, but oxygen eight times the mass of produced hydrogen could be produced at the same time. Energy requirements for conventional mining of rock or permafrost may or may not run as high as for in situ extraction of water, but the energy for dehydrating the rock or permafrost zone material and for electrolysis, liquefaction, and storage, will be just as energy consuming.

Paul (1965) has made a complete economic analysis of the problem of lunar resources utilization, confined largely to propellant manufacture. He states that "this paper will support a first order answer to the question of economic feasibility related to lunar propellant manufacture within the lunar exploration era of lunar activities."

Paul bases his calculations very heavily upon the demand for liquid oxygen. He sees this as the controlling factor. Most of this demand will be for (1) the support of lunar exploration and other operations and (2) the support of Mars and other inner solar system exploration. Most of the lox (and LH_2) would be for fuel purposes. He says: "Within the context of a reasonable projection of our space effort, it is difficult to postulate large demands of liquid oxygen on the basis of life support or mobility system requirements; it is necessary therefore to conceive a crew transportation system which can utilize lunar produced propellants for the

return trip to earth. - - - - since this crew transport vehicle would be refueled on the lunar surface with return trip propellants (or return lox only), it conceivably can carry cargo to the moon, in addition to men, equivalent to the mass of propellant required for return propulsive thrust. Obviously, this reduces the number of logistic flights required to support the expedition." The estimated LO_2 for one return flight is 15,520 pounds and of LH_2 , 3100 pounds. By allowing a spillage of 15 percent, Paul (1965) estimates a total oxygen demand of 10,000 pounds per month in 1976, projected to increase to 15,000 in 1978 and 20,000 tpm in 1982, based on an assumed crew size and rotation rate.

Paul (1965) did bring "rock acquisition" into his estimates. He says: "A limited amount of data is shown in Fig. 10 which can assist in the estimation of the manpower requirements for rock acquisition. Curves are shown for various specific gravity assumptions which convert a given rock acquisition rate into an appropriate manpower requirement. A few terrestrial analogues are indicated which might aid estimation. Published lunar 'soil' handling estimates, known to the author, are also referenced. With respect to the needs of this analysis, the rock handling rates shown on the abscissa must include the rock transport time from quarry to processing plant and vehicle 'dead time,' if any, in addition to the actual excavation time. It must be confessed that the actual design point chosen for this paper was based heavily on numerical convenience." He also estimated the mass burdens for two pieces of soil handling equipment (front loader or back-hoe, at ~ 6.8 and 8.6 kilopounds) from two of the references referred to, above. A third plot shows rock requirements as a function of lox demand for 1, 2, 5, 10, 15 percent water content in rock, permafrost with 50 percent water and rock for the carbothermal reduction process (apparently ~ 40-45 percent oxygen). The "soil" handling references mentioned were from NASA contractors, dated 1965, and are

not available. They are from contracts for lunar exploration systems for Apollo (LESA). The quotation, above, with regard to choosing values "based heavily on numerical convenience," was corroborated in private conversation between Mr. Paul and one of the authors. He stated that one of the gaps in lunar resources cost estimates is the operating cost range of various mining systems.

If lunar water is found as surface ice in caverns, etc., or even as high water content permafrost within 10-20 meters of the surface, acquisition of raw material should constitute a relatively minor part of total oxygen and hydrogen costs. If, however, ores are lean, or relatively inaccessible from good lunar base sites, or deep, or with a deposit geometry requiring a complex mining system, raw material acquisition will prove an important part of the total cost. Byproducts such as construction materials, etc., probably will reduce the net cost but little.

Certain other charges may also be applicable to lunar mining operations. The most important of these is at least a part of the cost of exploration for water. There is little doubt that the lunar surface will be explored, whether or not water is found. Water deposits could very well be discovered during Apollo or post-Apollo exploration or by some of the early scientific drilling. If this does not happen and specific water exploration work is initiated, the cost should certainly be a charge against lunar resource utilization.

Another possible charge is for part of the development of lunar surface transportation and communications systems for all purposes. Undoubtedly, the prototypes of transportation vehicles will be developed during the post-Apollo lunar exploration period and before any sort of mining operations start. Continuous systems like pneumatic pipe lines, aerial tramways, track systems, etc., for mine-to-mill transportation might, of course, be developed solely for mining operations and be fully chargeable to them.

A ten year program of lunar exploration has been proposed, beginning with the first manned landing, and divided into 3 phases: (1) the early Apollo missions (2) Apollo Extension System (AES) missions (3) Post-AES missions (Allenby, 1965). If the initial landing is in 1969, exploration efforts are planned no farther than 1980. If promising water sources are discovered any time during the first two stages, primitive and small scale mining may begin during the third one. Paul (1965) estimates the first quasi-permanent lunar station for 1976, and mining could hardly begin prior to that date. Paul's estimated raw material demand at that date would require about 520 kilopounds of rock with 2 percent water or about 120 kilopounds of rock with 10 percent water. These figures give the approximate magnitude of earliest lunar mining operations if they are to supply all or a major portion of the lox demand. If a rich ore like 50 percent water permafrost is found, the rock requirement is vastly reduced (~ 25,000 pounds).

When the stage of extensive inner solar system exploration is reached, if the low gravity moon proves to be the ideal launching platform and chemical propulsion is still exclusively used, the LO₂ and LH₂ demands may greatly exceed figures quoted so far and thus stimulate really extensive lunar mining operations.

III

LUNAR GEOLOGY AND THE OCCURRENCE OF WATER

The extent and mode of occurrence of water, ice or hydrous mineral deposits near the lunar surface will depend upon the geology and geological history of the moon and this, in turn, may be heavily dependent upon lunar thermal history. At the present state of our knowledge, the basic principles as well as of the details of lunar geology are a great question mark.

The primary geological problem upon which there still is fundamental disagreement is the origin of the lunar surface features, especially the maria and the craters. There are two rather extreme and conflicting views.

(1) The first is that the major surface features resulted from the impaction of large external bodies, that the larger impacts were accompanied by much melting, and that these events happened toward the end of accretional growth of the moon or early in lunar history.

(2) The second is that all surface features are endogenous, resulting from the escape of gases, vapors, liquids and molten rock, in some form of volcanism and may have occurred from early lunar melting or from later radioactive heating. Of course, in addition, many combinations of external and internal forces may be pictured as producing any observed or inferred surface features and structures.

If there is anything like a consensus regarding the origin of lunar surface features, it appears to include at least the following conclusions:

(1) The vast majority of the large craters and more than likely all the circular maria basins, were formed by impact of external bodies.

(2) The maria were filled by lava from the lunar interior, the flow of which was induced or "triggered" by deep fracturing due to the larger impacts. Alternatively, the maria were filled with fluidized ash flows (not falls) resulting in layered tuffs (O'Keefe and Cameron, 1963).

(3) Some form of outgasing has occurred and is now occurring. Some of the smaller craters, including all chain craters, have resulted from outgasing, if not from volcanism, earth-style.

(4) There is little or no evidence for structures resulting from tectonic or compressional forces nor do there seem to be laterally displaced surface fractures.

(5) The chances for sizeable ice or hydrous mineral deposits are much greater if the volcanic theory of lunar feature origin proves correct than if impact theories are verified.

The agreement regarding lunar thermal history is poorer than that for the origin of major features. McDonald (1961) found no chondritic lunar model which involved complete melting from radioactive heat, even with an initial temperature of 1200°C. Levin (1962) shows melting curves indicating essentially the same conclusion but he reasons that partial surface melting would take place anyway. Some surface melting or long continued transport of silica and other light elements toward the surface by fluids, is usually invoked to explain the differentiation of the earth's crust. Most geologists feel that the moon must also be differentiated and hence, that complete or almost complete, melting must have occurred at some time in lunar history. Recently, Donn, et al (1965) advocated an exogenous origin for the earth's crust. Shotts (1966) argues that a differentiated lunar crust, unless produced by very early melting, is not likely. Early melting would make less plausible extensive volcanism during later stages of lunar history, including the time of formation of younger craters and other features.

Loomis (1965) has made an excellent and detailed summary of possible lunar petrologic models. He lists six basic rock types, depending on degree of differentiation and to some extent, on elemental abundances. He assumed differentiation from none to quite advanced. Shotts, et al (1963) suggested three general lunar

models as to origin, but were not specific as to rock types. Lowman (1963) and O'Keefe and Cameron (1963) are strong advocates of differentiated highly silicic surface rocks such as granites or rhyolites.

1) For a "cold" moon with little or no internal melting, there should be no rock differentiation and ultra mafic rocks should be predominant. Olivine and pyroxene, as in meteorites, should be the principal minerals. Again, as in meteorites, rock chemistry should represent a more reducing environment than on the earth. For example, virtually all iron should be ferrous and all sulfur free or sulfide.

High pressure phases such as pyrope garnets and olivines with spinel structure should be abundantly present if the moon were ever part of a larger body (Loomis, 1963) or perhaps would occur sparsely from the effects of impact pressures.

2) For a "hot" moon subjected to very early melting during accretion, or as a result of short half-life isotope activity, some differentiation would have occurred.

If the melted period were short, with little time for fractionation, basalts should predominate; if the period were longer, trachyte or granitic types would result (Loomis, 1965).

Loomis (1965) suggests two rock suites resulting from extensive differentiation: 1) alkaline differentiation with slow silica concentration and 2) alkaline earth differentiation with rapid silica concentration. In the first, basalt will be most common but also present would be low-silica hawaiite, phonolite and trachyte. In the second, there should also be basalt accompanied by high-silica dacite and rhyolite. As the latter rocks on earth occur prominently in orogenic belts, the apparent lack of such belts on the moon render their lunar occurrence somewhat less likely.

Finally, the possibility that the maria originated as lava flows from the lunar interior, make it probable the rocks in these areas are relatively undifferentiated and have compositions similar to that of chondritic meteorites (ultrabasic).

For purposes of simplification, two compositions will be considered as possible for lunar surface rocks: granites and similar silicic rocks, and basalts and similar basic rocks. If the moon has a chondritic composition and is undifferentiated, the basaltic composition will have to be that of dunite or peridotite to give the overall lunar density of 3.34 gm/cm^3 . Models for ice or hydrous mineral deposits were selected with both outgassing and impact theories in mind. Frankly, this writer believes that lunar geologists have been overwhelmingly partial to volcanism which provides a relatively easy case for water occurrence; therefore emphasis has been placed on impact models more than is usually done. Some outgassing, however, even if very mild and secondary, must be assumed if deposits of any size or of more than a random distribution (i. e. groups of deposits or "districts"), are to be anticipated.

There is near unanimous agreement among lunar scientists and technologists that water will be the primary mineral sought and utilized on the moon by lunar colonies or exploration expeditions. The way in which water occurs, will be the primary factor in the determination of its abundance, its accessibility and the cost of its utilization in terms of dollars, equipment and manpower.

Water may occur in the form of (1) free water or (2) as water-or hydroxyl - containing minerals. Occurrence in the form of free water as pure ice or as massive ice mixed with soluble salts, rock fragments or condensed vapors, would minimize cost and the energy required for its recovery. Water physically absorbed into the pores of volcanic tuffs, pumice, rubble, etc., would probably be in the range of energy required for next economical recovery. Water in the form of

molecular water of crystallization as, for example, in gypsum, $\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$, requires less recovery energy than does hydroxyl - containing minerals like serpentine, $\text{Mg}_6\text{Si}_4\text{O}_{10}(\text{OH})_8$, or topaz, $\text{Al}_2\text{SiO}_4(\text{OH}, \text{F})_2$. Probably the most expensive water, but that with the greatest probability of widespread occurrence, would be that extracted from average lunar rock with no particular water enrichment. Common earth igneous rocks have been shown by Green (1960) to average no more than one percent water (recoverable at temperatures $> 110^\circ\text{C}$). Some individual values were: average alkali - rich olivine basalt, 0.6 percent; average alkali andesite, 0.8 percent; average alkali rhyolite or rhyolite obsidian, 0.6 percent; and average phonolite, 1.0 percent.

A. Free water (ice) deposits: The ultra-low lunar atmospheric pressure and high lunar daytime temperatures preclude the presence of water in any form on the visible lunar surface (Green, 1960). The principal areas of eternal shadow within which surface ice may be found are (1) certain deep craters near the lunar poles, like the crater Newton near the south pole and (2) within caves or lava tunnels on the maria. Watson, et al (1961), have presented the case for water in perpetually shadowed craters at high lunar latitudes. Green and Van Lopik (1961) have discussed the possibility of ice in volcanic, surface - connected, but shadowed, tunnels and caves.

In both cases, it is recognized that the existence of ice will depend upon the true lunar atmospheric pressure. At the probable minimum lunar surface temperature, $\sim 105^\circ\text{K}$, the vapor pressure of water is about 10^{-12} torr. Recent estimates of lunar atmospheric pressure are from 10^{-9} to 10^{-13} earth atmospheres or from 0.76×10^{-6} to 0.76×10^{-10} torr. In MKSA units the lunar atmospheric pressure varies from 1.013×10^{-4} to 1.013×10^{-8} Newton/ m^2 and the vapor pressure of water is about 1.33×10^{-10} Newton/ m^2 at 105°C . Thus, if the lunar atmospheric

pressure is no lower than 1.013×10^{-8} Newton/m², ice may exist. If, however, it is lower than $\sim 10^{-10}$ Newton/m², all ice should evaporate in time.

A possible source of surface free water, independent of atmospheric pressure, would be vapor in sub-selenian emissions. Kozyrev has detected such emissions at very low pressures (Alter, 1959; Urey, 1961) but no water vapor was detected. Unless water vapor pressures in emissions are considerably higher than lunar atmospheric pressures, it will take an infinite length of time to "harvest" an appreciable quantity of water from this source.

Free water, as ice, is much more likely to occur under the lunar surface at depths of a meter or more (Salisbury, et al, 1963). The near surface temperature of the moon has been estimated, from radiometric measurements, to be from -23° to -53°C , averaging about -40°C (233°A). Under this condition, water rising toward the surface from the interior will be condensed to ice and any subselenian free water will be in the solid state. This may be in the form of fissure or crack filling (veins), saturated pore space in volcanic tuffs or breccia, or in buried rubble layers from meteoritic impact.

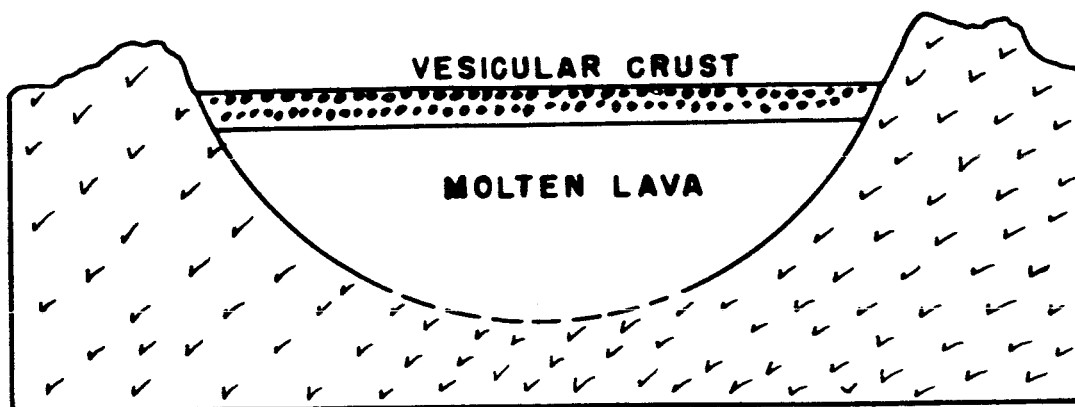
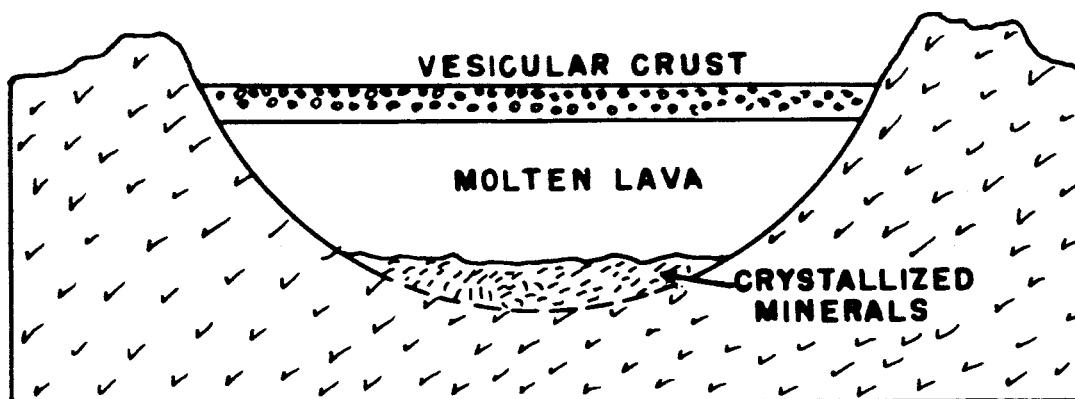
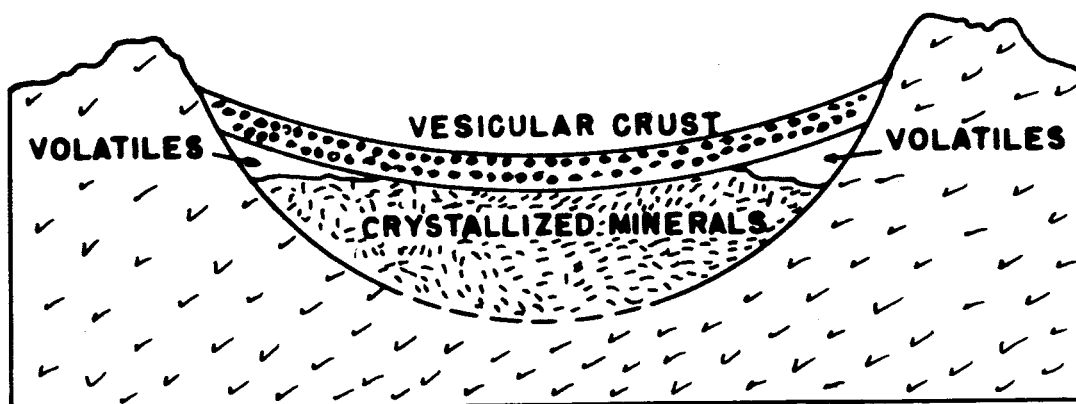
On the maria, water should have accompanied the flows of lava with which these features (and a few craters) may have been flooded. In this case, structural modes of entrapment may be prominent and water may occur also in vesicles of lava expanded in the lunar vacuum.

A number of geological models for the sub-surface occurrence of water on the moon have appeared in the literature. The great majority of these imply an endogenic origin for lunar surface features and the models are greatly influenced by earth analogies of volcanic origin. Some of the volcanic models will be discussed and a few others, based largely upon impact origin of craters and lava origin of maria, will also be advanced.

1. Entrapment of volatiles near the mare margins. This model (Fig. 1) has been suggested by Salisbury (1962). Water and other volatiles could escape entrapment under certain circumstances so that drilling or other exploration of these "reservoirs" occasionally may result in "dry holes". This first model, oddly enough, is independent of the origin of the lava whether from endogenous sources or from impact heating. One possible difference would be that endogenous sources could provide a succession of flows rather than one big one probably required if impact heating is assumed. If impact merely "triggered" the lava flow from the lunar interior (Kuiper, 1959) rather than produced the melting itself, more than one flow would be possible but the initial one should be the most important. Successive flows could produce multiple "reservoirs," one above the other.

2. Fig. 2 is one of the 8 water-occurrence models of Westhusing and Crowe (1964). It represents a mare crater. The mare is made up largely of layers of tuff with rubble on the surface. Also shown is a layer of premare rubble on a massive granodiorite surface. The zone of possible economic interest is the permeable tuff carrying water. The mare crater with the fracture zone below is of impact origin.

3. Fig. 3, another Westhusing and Crowe (1964) model, is the faulted left side of the previous model. Water has risen along one fracture and has migrated into wall rock, the pre-mare rubble layer, and the welded tuff. Rapid cooling in the vertical direction, as well as heat abstraction by the colder beds as the water travelled laterally, may result in the deposition of minerals and soluble salts. Near the surface, the water would freeze and as the solutions cooled, freezing would be attained to greater depths.

**PHASE 1****PHASE 2****PHASE 3****FIG. 1**

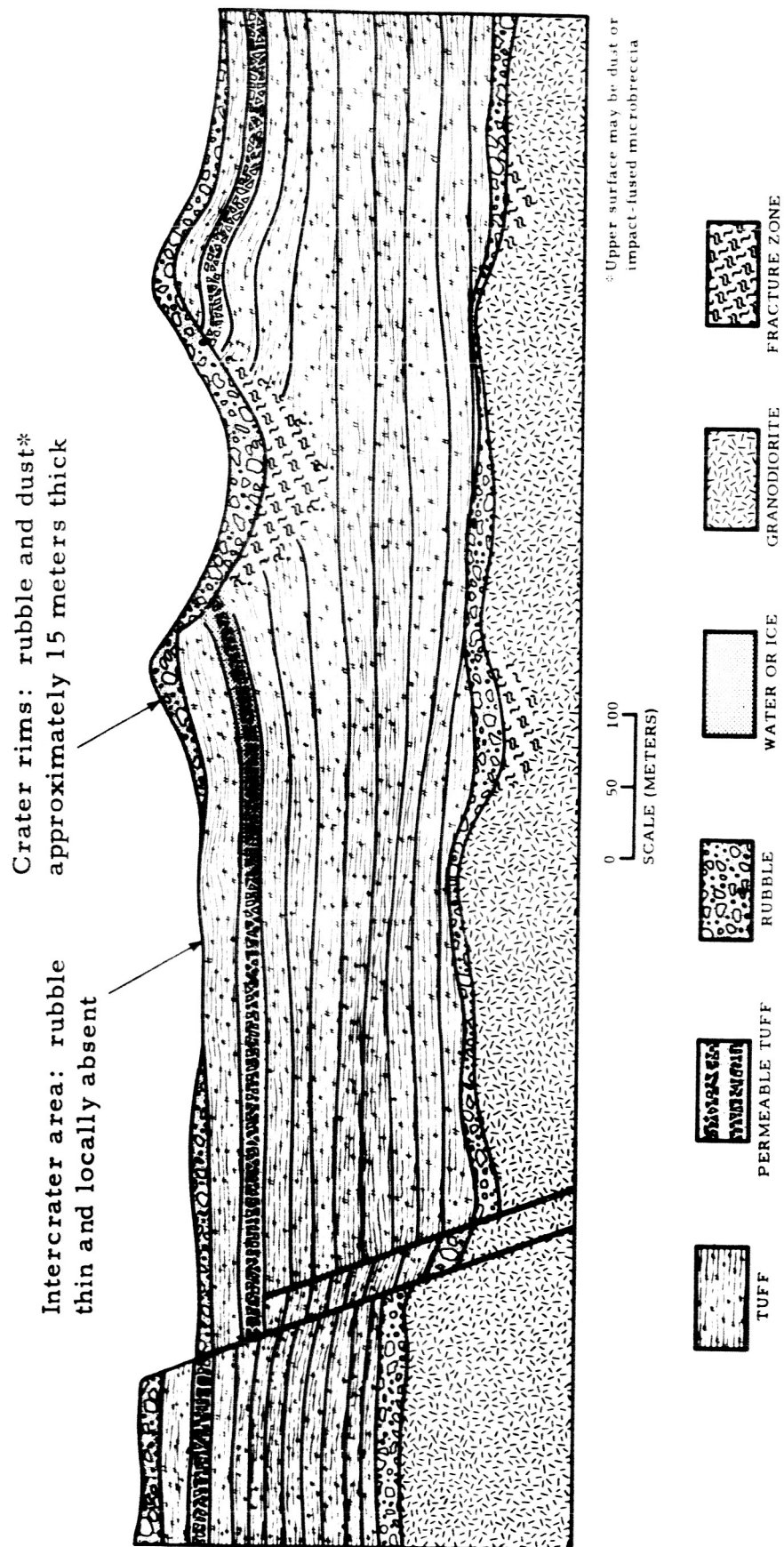
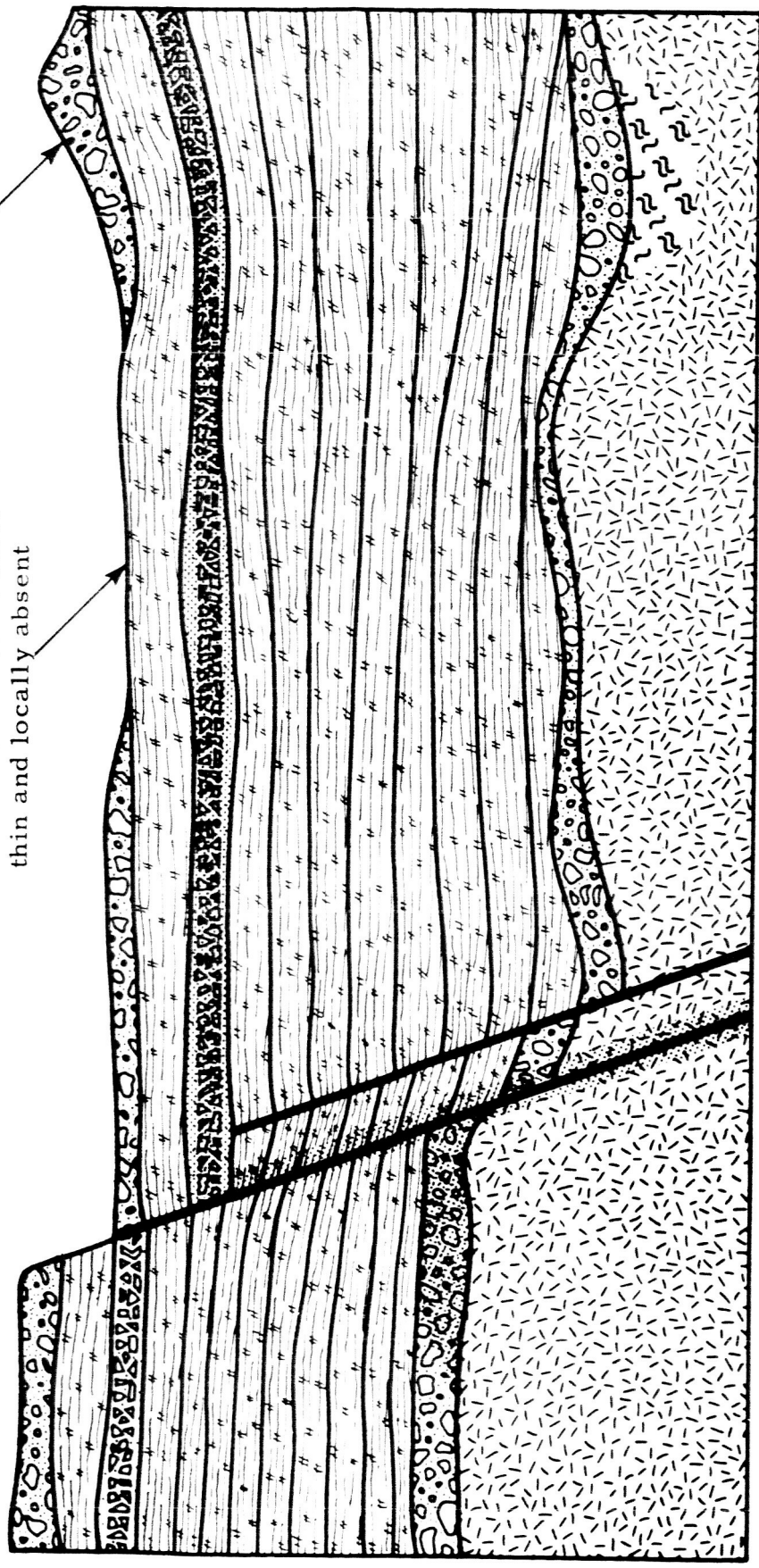


FIG. 2

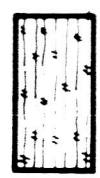
Crater rims: rubble and dust*
approximately 15 meters thick

Inter crater area: rubble
thin and locally absent



*Upper surface may be dust or
impact-fused microbreccia

0 50 100
SCALE (METERS)



WELDED TUFF



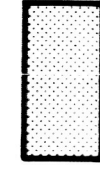
PERMEABLE TUFF



RUBBLE



FRACTURE ZONE



WATER OR ICE



GRANODIORITE

FIG. 3

4. Westhusing and Crowe (1964) give Fig. 4 as a model of a highland crater. It is obviously of impact origin in "original" granodiorite with a cover of rubble from later impacts. The fractured zone contains water or ice as well as thermally altered granodiorite (clays).

5. Fig. 5, also from Westhusing and Crowe (1964), is a model of a highland area. A permafrost zone is shown with little or no indication of the source of the water in the zone.

6. Fig. 6 is a model based upon the assumption that the maria are lava flows. This model assumes a major shrinkage or tension crack (rille), possibly parallel to the mare margin, as can be seen in photographs of Mare Humorum. Volatiles rising from the hotter parts of the deep lava filling have condensed in the impact rubble with which the crack slowly filled. It is true that if molten lava existed, at depth at the time the cracks were formed, they would be partly or completely lava-filled. It is assumed in this model that the rille is not filled or is incompletely filled by lava.

Deep in the rilles, the steam may be hot enough to hydrate certain minerals, but higher up the steam cools below reaction temperatures, condenses and freezes.

7. Fig. 7 is a model depicting both a transverse and a longitudinal section across chain craters. A plan view is also shown. It is based on the assumption that chain craters form along fissures or cracks in the lunar surface. At various places along the fissures, gases and vapors are expelled gently or violently, throwing out the rubble filling the cracks at certain points while the rubble remains relatively undisturbed in the other sections of the crack. If much large rubble is expelled, a crater rim will be formed; if the rubble is fine the rim may be low or missing. After rubble expulsion ceases, material slides or falls back into the crater. Rubble blocks too large to be expelled and others that fall or slide in

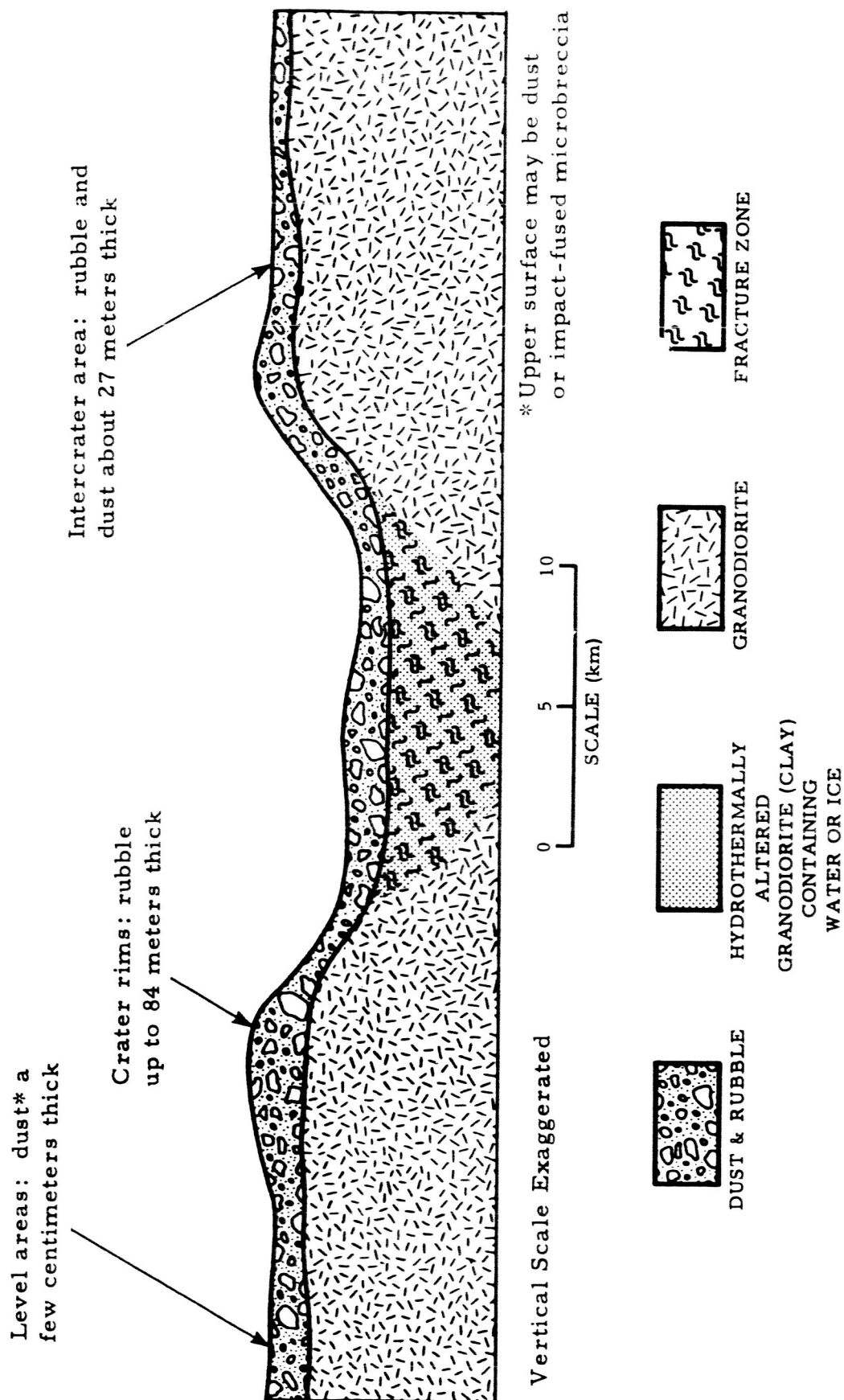


FIG. 4

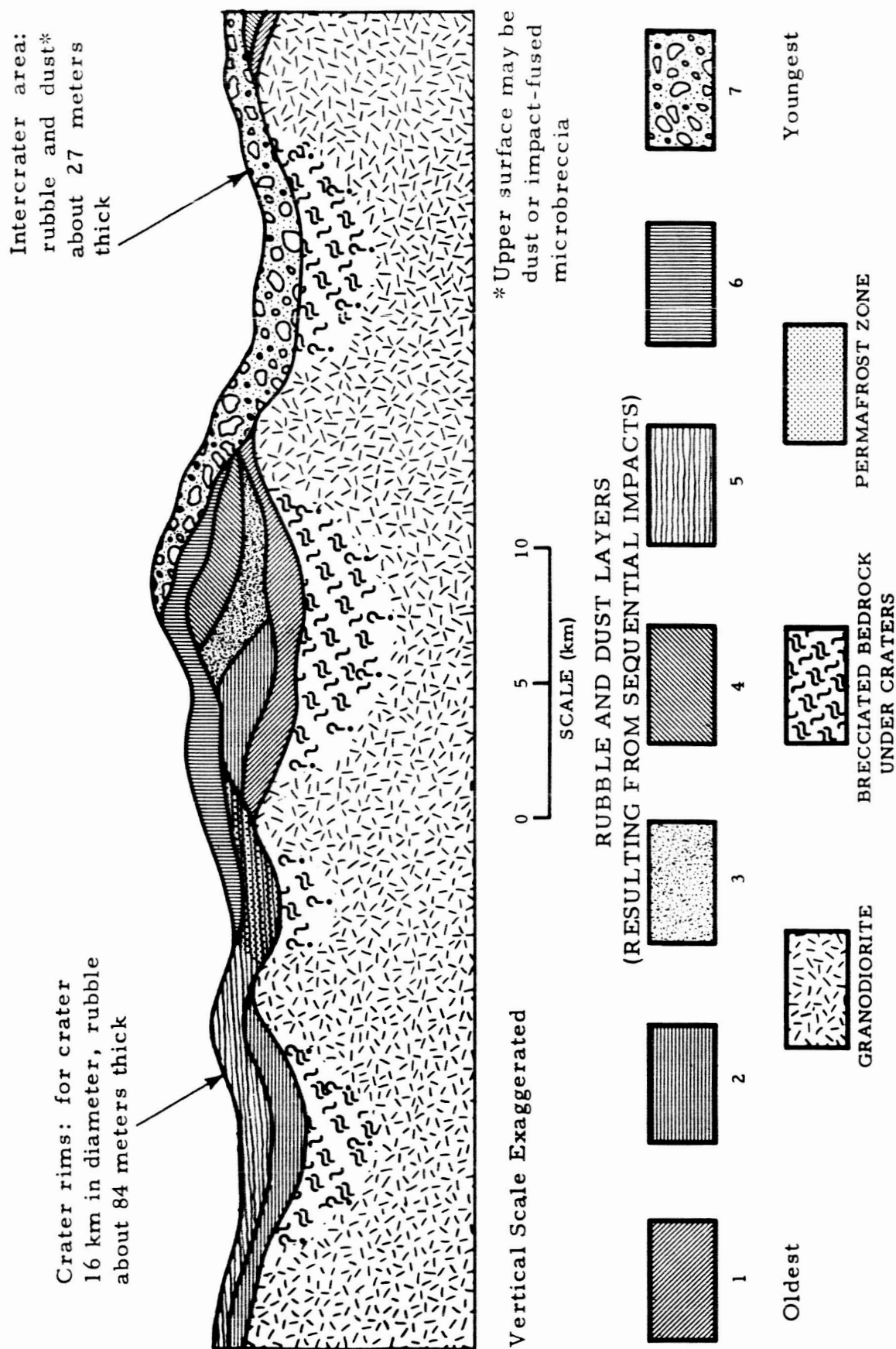
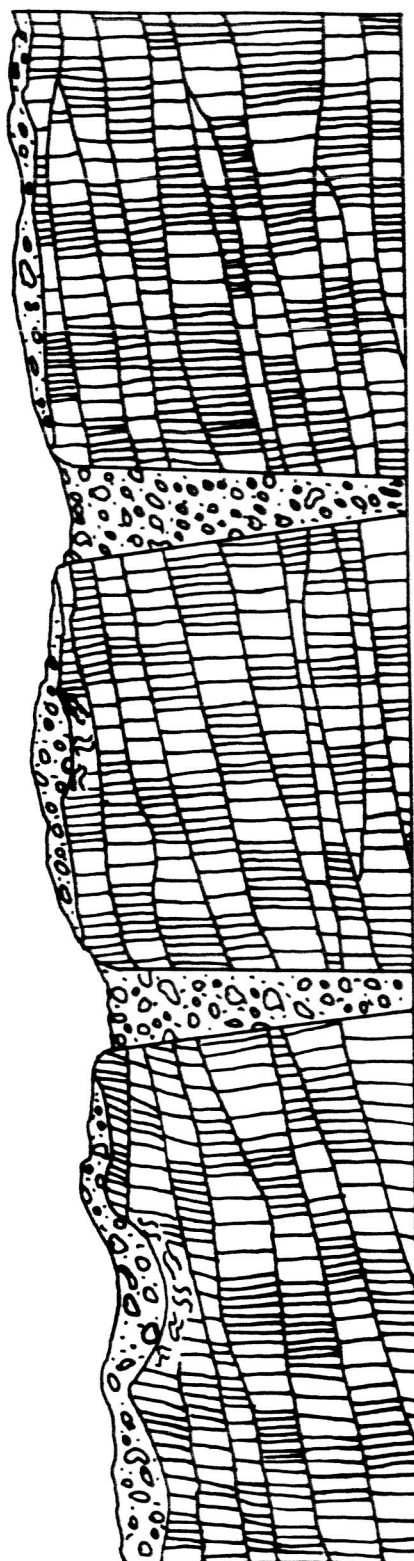


FIG. 5



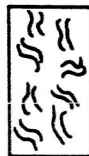
TRANSVERSE SECTION



BASALT

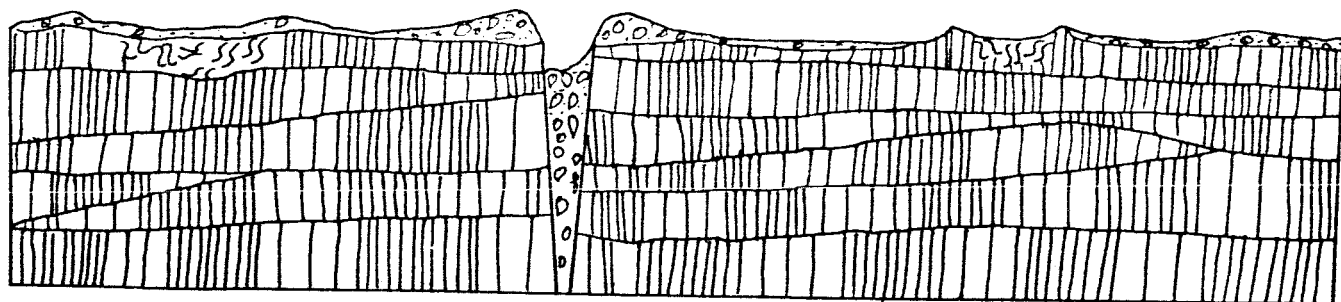


RUBBLE

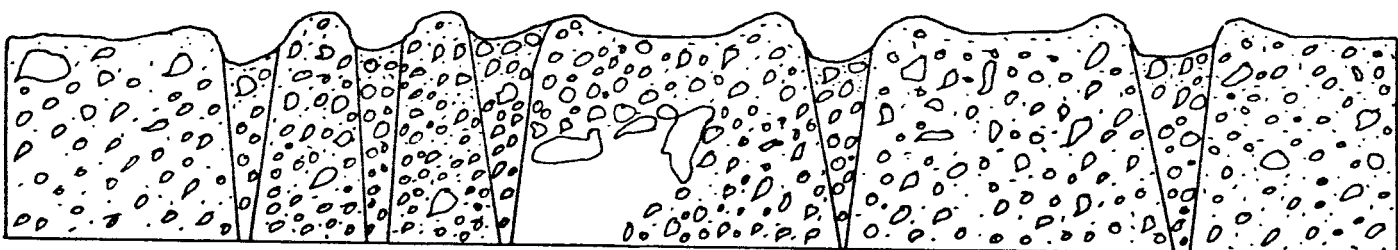


FRACTURED ZONE

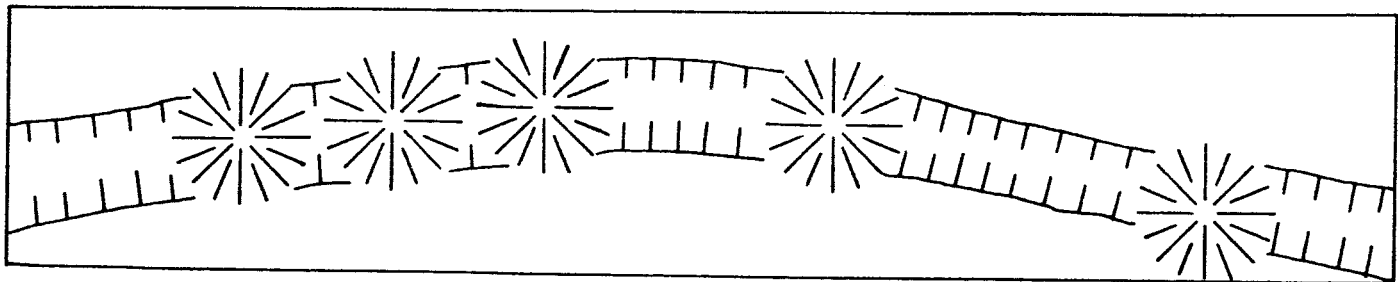
FIG. 6



TRANSVERSE SECTION



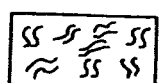
LONGITUDINAL SECTION



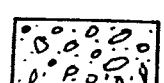
PLAN SECTION



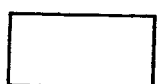
BASALT



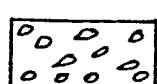
FRACTURED
ZONE



RUBBLE
UNSORTED



VOID



RUBBLE COARSE,
FEW FINES

FIG. 7

after the crater is formed will remain in the bottom of the crater, as indicated. During the late stages of degassing, water, if present, condenses in rubble and its freezing will further restrict the passageways available for continued gas evolution.

This model can apply to maria, highlands or to thick rubble areas like that in the vicinity of Copernicus. Chain craters along well defined cracks are more conspicuous on the younger maria but the relation may be as close, although hidden, in highland areas.

The explosive stage is not absolutely necessary for this model. If a crack became loosely filled with post-mare rubble which, in certain places slumped or dropped deeper, allowing material higher up to drain downward into the crack, a cone or funnel could be formed. Such a funnel would not, however, have a raised rim and issuing gases would not be required. In such a case, rimless chain craters might not represent a potential water reservoir.

B. Hydrous Mineral Deposits: If the moon proves to be very low in total water content, as a result of extreme devolatilization or because of cold accretion of low-water material, the most likely form of lunar water is as hydrous minerals with the water predominately in hydroxyl form. The apparent rigidity of the moon has been ascribed to its low water content (Orowan, 1964).

When considering models for the occurrence of hydrous minerals, the previous models for free water are also applicable with the exception of those involving permafrost or ice-impregnated fragmental material. Thus Model 1, above (Salisbury, 1962), could have hydrous minerals rather than ice around the edges of the maria. If water is relatively scarce in the lava, hydrous minerals might be the principal, if not the only, water form.

The hydrous zone along the large fault in Model 3 could consist largely or exclusively of hydrous minerals. Of course, in this case, the permeable tuff zone might or might not have water in it.

Model 4, of the highland crater (Westhusing and Crowe, 1964), probably infers hydrous minerals rather than free water. The water source might be the very low water content of "original" lunar rock or of an impacting carbonaceous chondrite or frozen volatile cometary fragment. In either case, the heat of the impact probably would result in hydration of minerals present (e. g., olivine to serpentine) rather than in the liberation of free water.

Models 6 and 7 could contain hydrous minerals as a result of the reaction between hot water vapor and certain minerals in the rubble, but such occurrence would be limited to the deeper parts of the cracks because water in the upper parts would be at a temperature too low to react.

8. Fig. 8 (Westhusing, et al, 1964) is a general model of lunar surface rubble. The serpentine boulders probably were dislodged from the lunar surface, although serpentine occurs in meteorites. Large and probably small meteorites as well would vaporize or fragment on impact and no boulders of appreciable size would survive. This model constitutes a rather lean and erratic "ore" deposit. Surface mining would be about the only practical method applicable.

9. Salisbury (1961) has suggested that lunar domes may occur as the result of an increase in volume where ferromagnesian rocks of lunar maria were hydrated by ascending waters. Fig. 9 shows how masses of serpentine might develop above the 500°C isotherm by the reaction of water from the lunar interior with peridotite rocks of the maria. Because from a mining standpoint the 500°C isotherm is likely to lie at considerable depth such deposits of serpentine are likely to be relatively inaccessible.

Westhusing and Crowe (1964) also have a model of a lunar dome which is shown in Fig. 10. Their model is based on the laccolith theory of dome origin. Hydrous minerals should be present in the laccolith but it seems unlikely that the water content can be high.

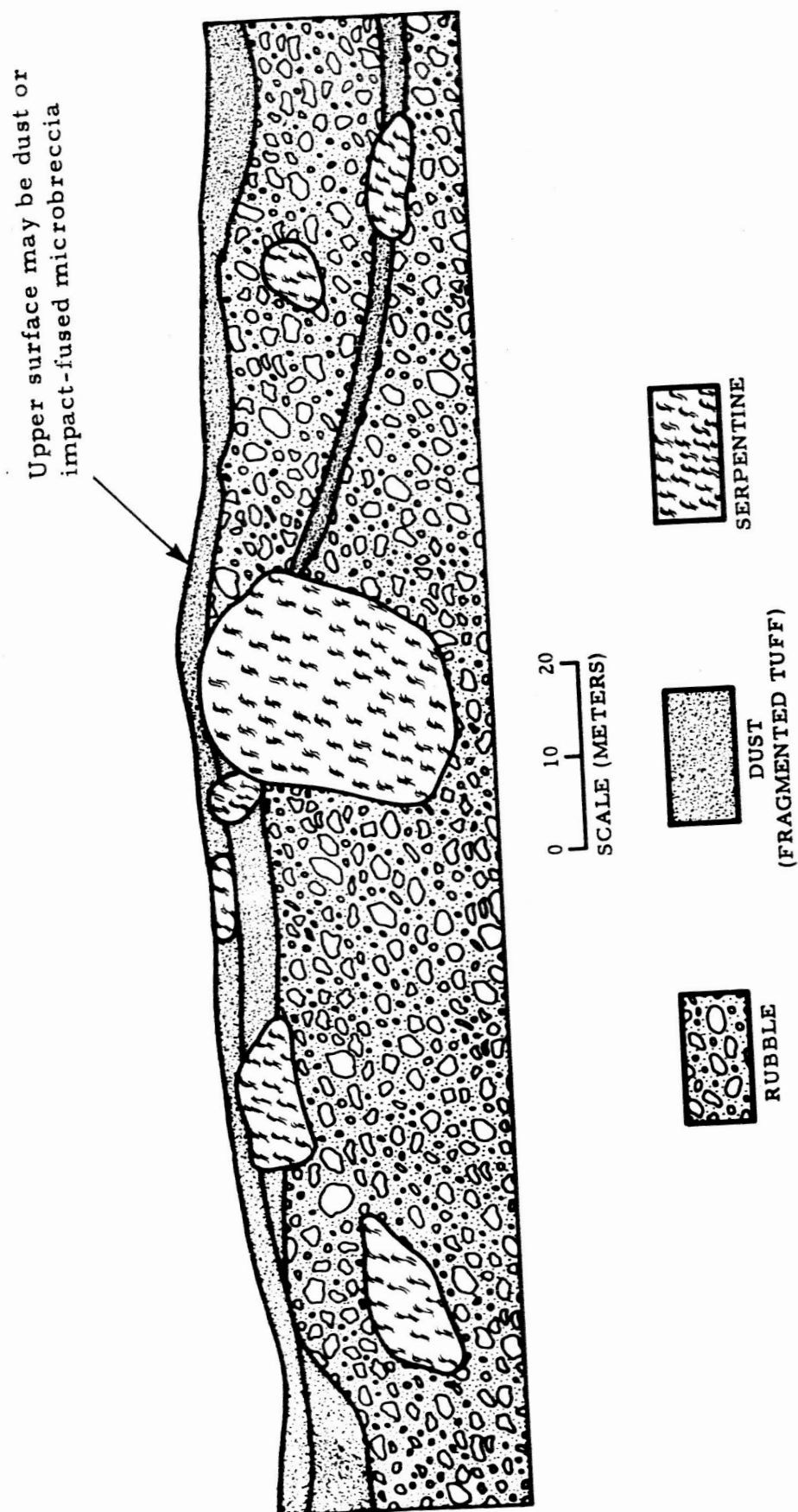


FIG. 8

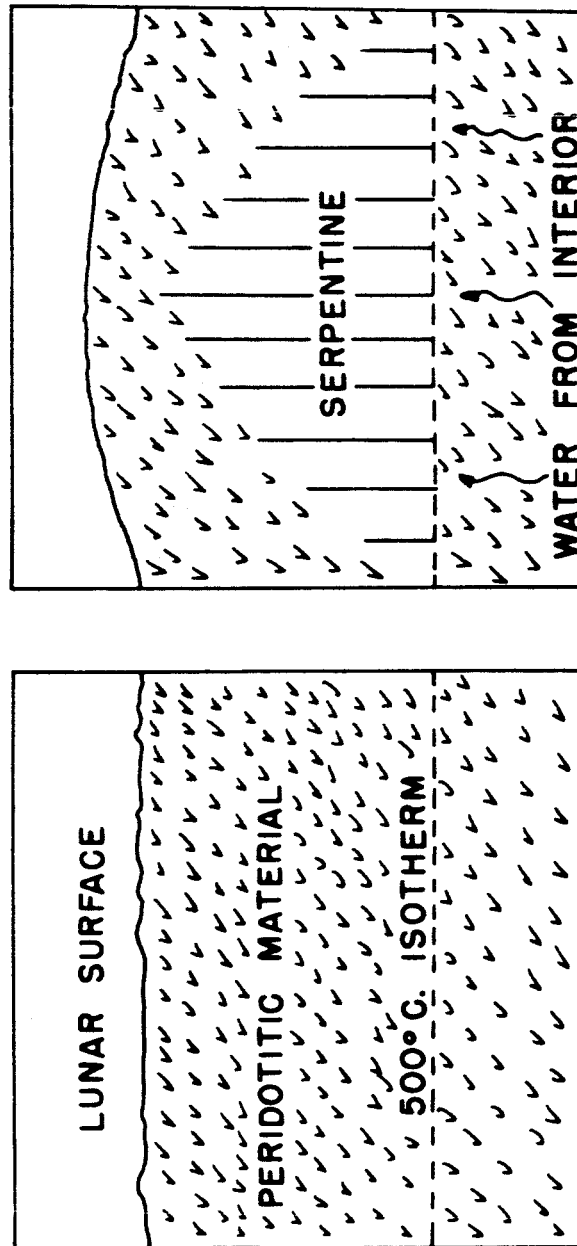
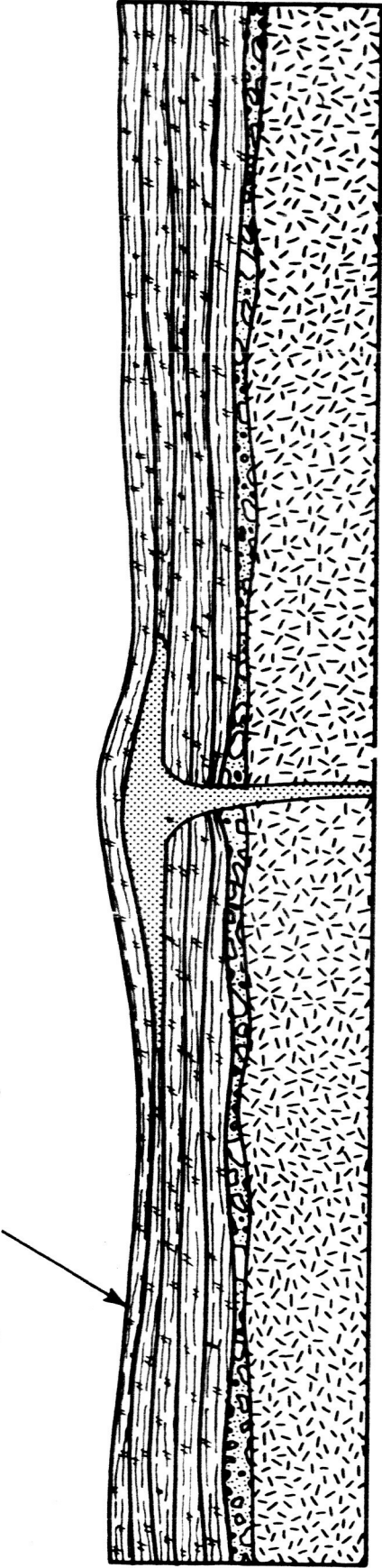


FIG. 9

Inter-crater area: rubble and dust*
about 0.5 meter thick, although
thin in places and locally absent



*Upper surface may be dust or
impact-fused microbreccia

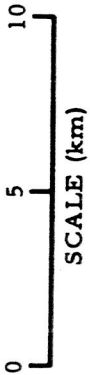


FIG. 10

11. Fig. 11 is a model of a lunar rille based on the assumption that it is a lava-intruded graben. The ore would contain hydrous minerals. This model, it will be noted, assumes the maria are basaltic flows rather than tuff as proposed in models 2 and 3, above. In this model it is probable that the ore is only slightly enriched in water.

12. Fig. 12 is the Westhusing and Crowe (1964) model of a chain crater. It is a lava-filled cone and apparently has no explosive stage as did our model, Fig. 7. Because of its intrusive origin (with block faulting) this would be a reservoir similar to model 11.

In addition to the 12 models for localities for possible water enrichment, all earth rock types and presumably lunar types also contain some water.

Westhusing and Crowe (1964) give the average water content of the rock types specifically shown in their 8 models, all of which are included above in the twelve models. Water content of the rock types is shown in Table 1.

The percent of SiO_2 in each rock type is included in Table 1 to indicate roughly the "acidity" of the rocks in the sense used by the petrologist.

It is quite probable that the water content of the earth's fragmental rocks and of the others, to a lesser extent, may be influenced by the relatively water-rich surface of the earth, a condition that may not now exist nor has ever existed on the moon. Basaltic rubble, for example, has 1.60 percent water. Green (1965) found 0.86 percent for a Columbia River tholeiitic basalt. Most of the different kinds of basalt analyses previously collected by Green (1965) averaged no greater than 0.86 percent. Lunar rubble formed in a water-free environment should contain only the water of composition of the mineral grains making up the rubble pieces and no more.

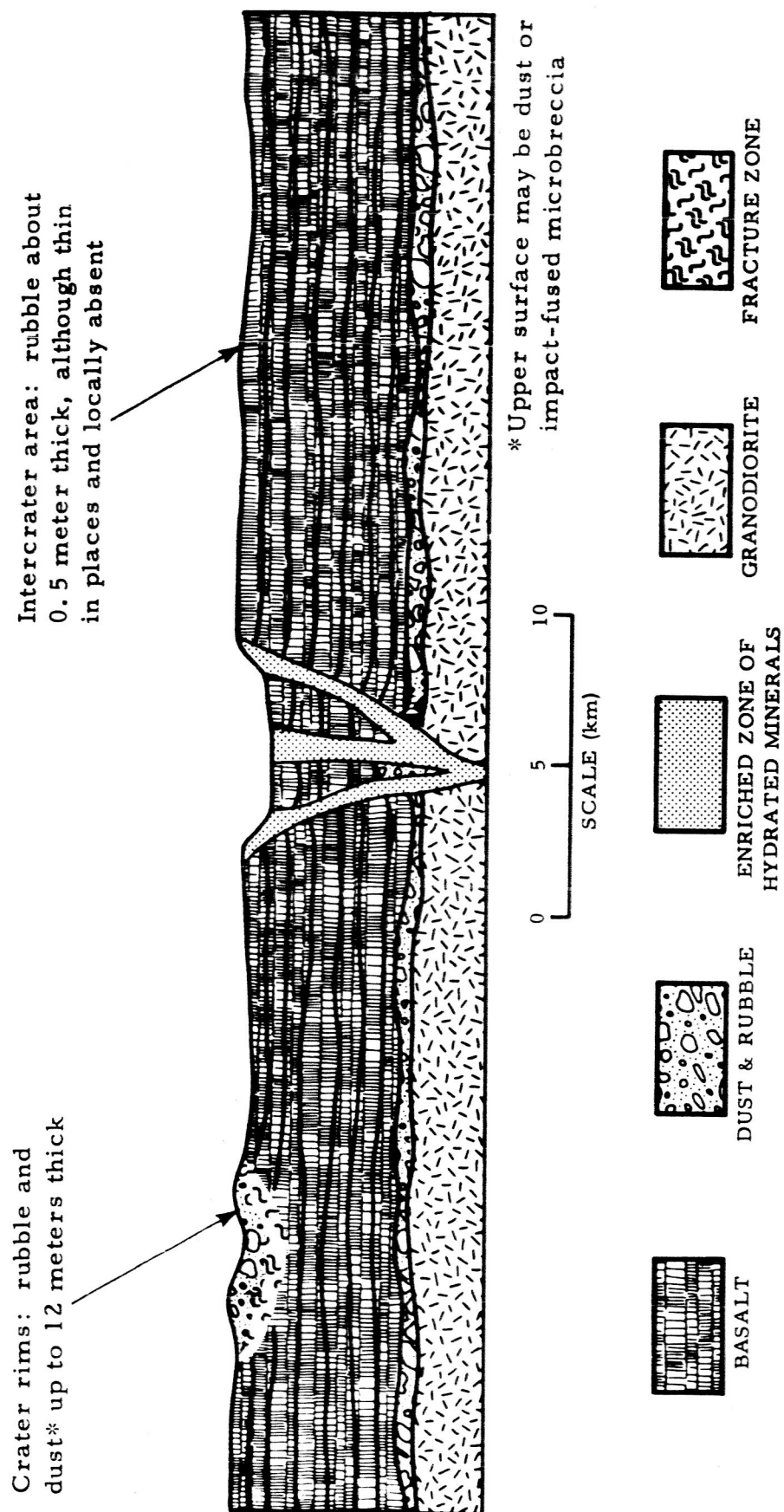


FIG. 11

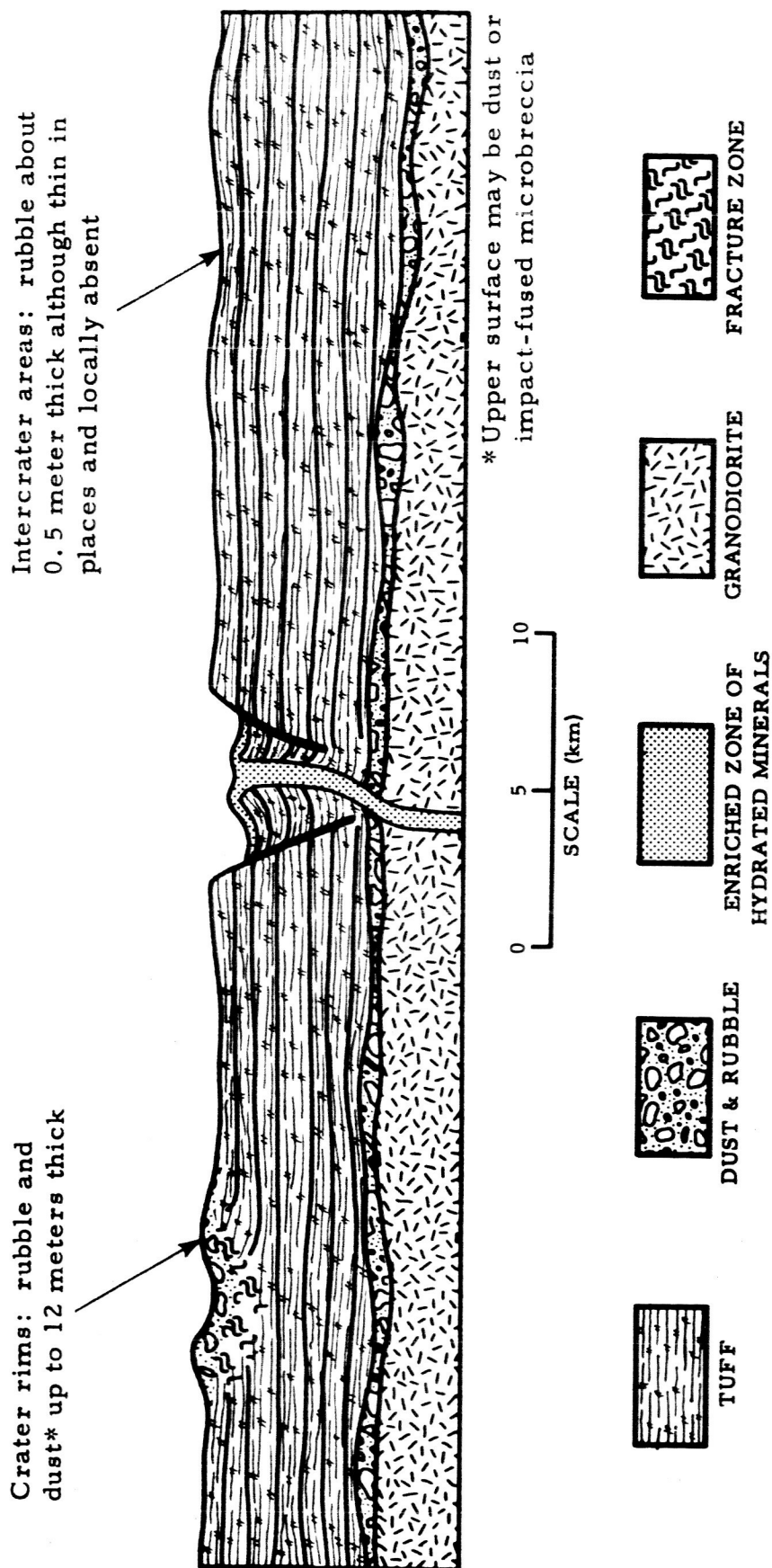


FIG.12

TABLE I

Average Water Content in Lunar Model Rock Types (Westhusing and Crowe, 1964).

<u>Rock</u>	<u>Percent H₂O</u>	<u>Percent SiO₂</u>
Granodiorite	1.0	65.0
Silicic Tuff (Rhyolitic)	0.8	70.2
Serpentine	10.7	40.4
Chlorite	11.0	26.0
Ice	100.0	0.0
Sericite (Illite)	8.4	48.6
Kaolin	13.0	74.0
Montmorillonite	19.8	52.4
Fe - Ni Meteorite	---	---
Chondrite	0.47	38.4
Granodiorite Rubble	0.95	60.6
Acidic Tuff Rubble	0.78	65.0
Basalt Rubble	1.60	46.9
Latite	1.30	57.8

IV

THE RANGE OF POSSIBLE MINING SYSTEMS

The cost and limited demand for water, either for fuel or for other purposes, will make it necessary that early lunar water mining be simple, on a small scale and at low cost. If accessible supplies of surface ice can be found in caverns, etc., near the lunar equator, no water will be mined in the usual sense of the term but will merely be "harvested." If, however, water is found only under the surface at depths too great to be affected by the diurnal (lunar) temperature cycle (about 1 meter), mining can logically be contemplated. As the demand for water increases, it is reasonable to expect the size and sophistication of the mining operations will increase. Figs. 13, 14, 15, 16, 17 and 18, using some of the proposed models for localities of water enrichment, illustrate possible trends in this direction.

Fig. 13 is a reproduction of our model 3 (model 2 of Westhusing and Crowe, 1964) and shows probably the simplest and most primitive mining system for the recovery of sub-surface ores. Lunar drills for shallow exploration are in active development at the present time (Delonis, 1966). This model employs the same drill for ore recovery as was used for its discovery. When the ore zone is reached, the drill simply goes on into, or through, the zone and the water-bearing ore is recovered from the drill hole and loaded for transportation to a recovery plant rather than sampled and discarded as was the drilled overburden.

Advantages of mining with the drill are that (a) some ore will be produced from the first hole reaching the ore body whereas, with strip mining, considerable overburden must be removed before ore can be loaded, and (b) exploration and mining are combined sequentially, by using the same equipment. The most obvious disadvantage is that production will be small and the operation thus rather inefficient

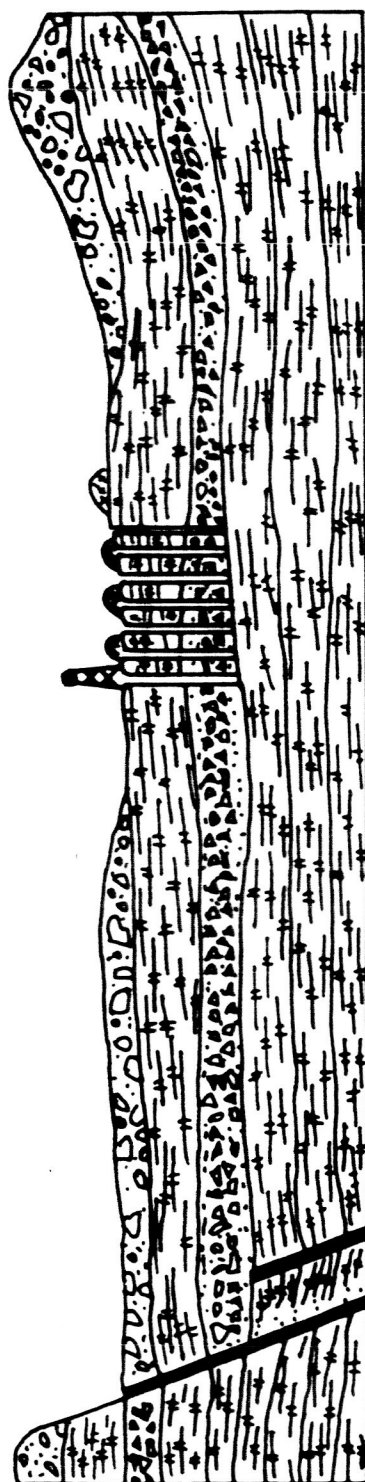


FIG. 13



RUBBLE



PERMEABLE

TUFF



WELDED

by earth standards. Perhaps mining with the drill will be practiced between the time of discovery of a shallow deposit and the importation of digging and/or loading devices from the earth.

A slightly more sophisticated mining system is the surface, strip or open cast method. In Fig. 14, model 3 is again assumed.

It is assumed further that the welded tuff layer, carrying ice, is at a comparatively shallow depth below the surface and that it is most readily reached in the intercrater area where surface rubble is thinnest. Westhusing and Crowe (1964) show horizontal scales on all their models and on some of them state that the vertical scale is exaggerated. This is not stated for model 3, so applying the horizontal scale to the vertical direction on the model, the permeable tuff layer is about 27m (87 ft.) deep and, adding the full depth of the ore zone, the strip pit would be about 53m (174 ft.) deep. This would constitute a rather formidable stripping condition on earth, even with large equipment. It is probable that, for the earliest lunar strip mining, the ore zone must be closer to the surface than indicated by these figures, or on the order of 5-10 meters. If ore is at moderate depths, if highwalls stand well as indicated in Fig. 14, and material is not too difficult to break and dig, strip mining using light equipment should be the most productive and simple system available.

The estimated density of dust or other porous upper surface material is 500 kg/m^3 and density of rubble is estimated to be 1700 kg/m^3 (see Table 2, Part VI). In a pit with overburden of 10m, 0.6m. would be underdense surface material and 9.4m. would be rubble. The mass of material over the ore, would be $500 \times 0.6 + 1700 \times 9.4 = 300 + 16000 = 16,300 \text{ kg}$ (35,900 pound or 18 tons) per m^2 of area. For excavation in solid rock overburden density would be about $2650\text{-}3250 \text{ kg/m}^3$. As the lunar gravity is approximately $1/6$ that of earth, the

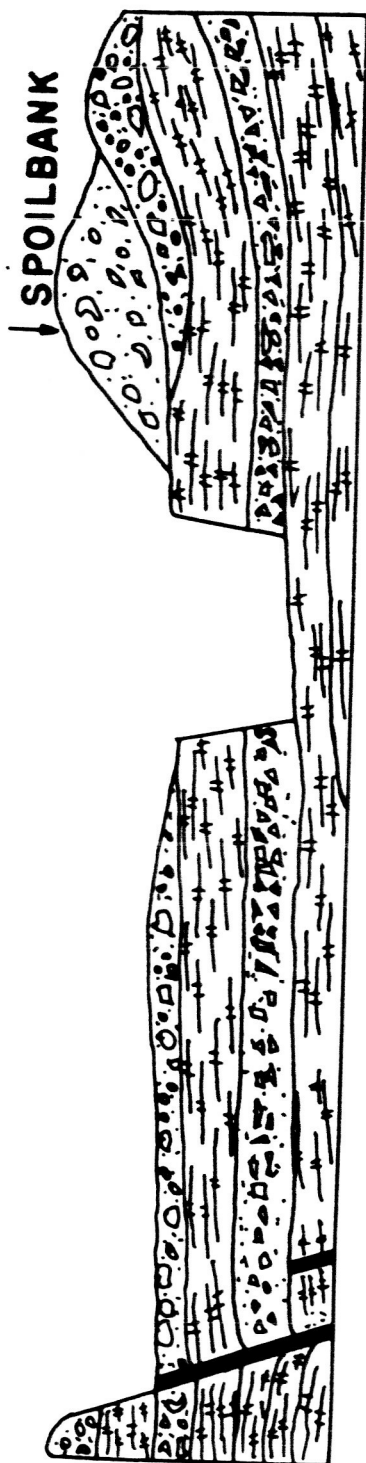


FIG. 14

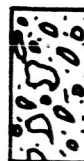


WELDED

TUFF



PERMEABLE



RUBBLE

weight of 10m of overburden over one m^2 of area would be about 2720 kg. (6000 pounds). Because weight of a given quantity of material to be moved is 1/6 of earth weight while the volume is the same, it is likely that a machine that digs and loads will be limited more in performance by its digging volume than by its loading weight, whether the loading is intermittent or continuous, and the material soft or hard.

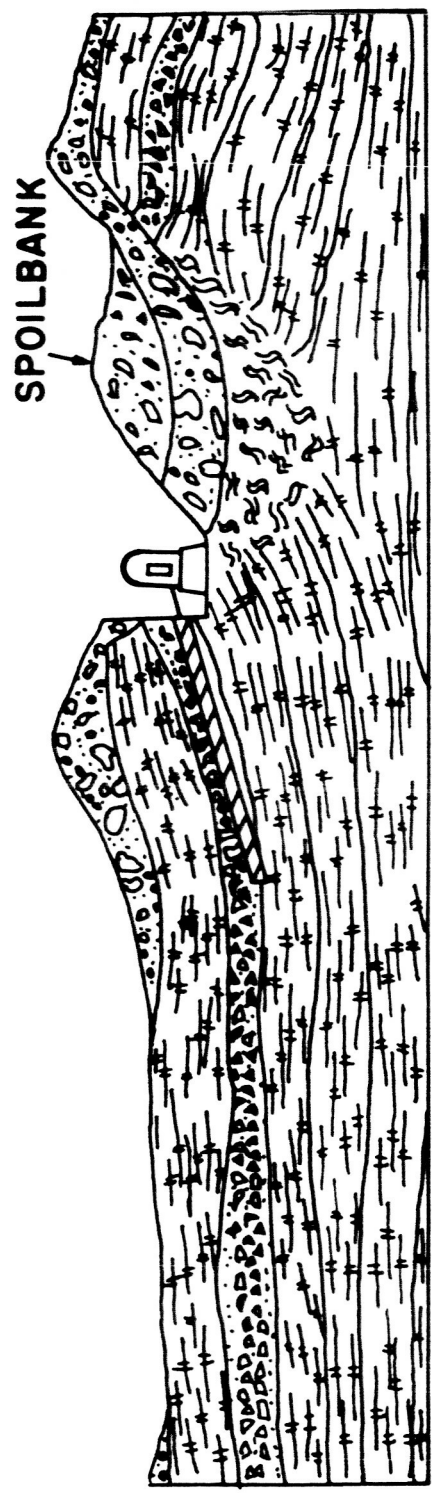
If high energy radiation proves too powerful or if the strip pit is so situated that the sun falls directly on the mining face, mining activity may have to be restricted to the lunar night period. A light shield over the working face would, of course, simulate lunar night and permit continuous work.

Strip mining operations would necessarily be limited to shallow deposits. At a later time, each model will be examined from the standpoint of mining methods that may be most adaptable.

Fig. 15 depicts model 2 being mined by a surface auger from a ramp built at the outcrop of the water-containing permeable tuff zone shown. Considerable rubble (over 10 meters) had to be removed to reach the bed.

There may well be some question regarding the ability of an auger to cut welded tuff, much as coal is cut in auger mining. Large boulders admixed would be the most formidable material to remove. On a terrain of impact origin, the bed would not be tuff but would be unsorted rubble, probably containing boulders and even sizeable masses of meteoritic iron. Under these conditions, auger mining would not be practicable.

Fig. 15 assumes an auger would cut the material and represents a more sophisticated mining system than strip mining because severance and loading can be combined into a single, continuous, fully automated operation. If surface mining is cyclic: overburden removal, severance (drilling, blasting), and loading, it is a little more primitive than auger mining. Both methods will be restricted to fairly



 FRACTURED ZONE

FIG. 15

shallow ore bodies, but surface mining probably has the fewer additional restrictions on its use.

Frasch-type mining methods from the surface also represent a fully automated method. Fig. 16 and Fig. 17 show two such proposed systems (Bensko and Shotts, 1965), both applicable only to free water. Fig. 16 is a system for ice mining by means of a circulating brine solution and Fig. 17 shows direct electrolysis of water, in situ. The latter probably would require some prior heating to induce melting because of the very high electrical resistance of ice. Applicable equally to free water or hydrous minerals would be thermal recovery, probably by bottom-hole heating with a SNAP-type atomic reactor (Salisbury, et al, 1963).

Fig. 18 represents a more primitive but more universally applicable method and one with more independence of the physical environment and of the nature of the deposit. Because of cost, complexity and manpower required, however, it probably will be the last method resorted to and is here classified as the most sophisticated.

The model is modified from model No. 1 (Salisbury, 1962) and is that of a small mare or a lava-filled crater. Specifically, it might be the crater Wargentien which apparently is filled to the brim. It differs from Salisbury's model in that the crater is of impact origin with a large fractured zone under it (Model 4 of Westhusing and Crowe) and with a rubble layer deposited over it before flooding. Salisbury, in his model, is non-committal as to the origin of the crater. The mine on the right is entered by a slope driven on the rubble layer as the footwall. The water enriched mineral zone would be mined, probably by some modification of overhand stoping.

The water, or hydrous minerals, occurring in the fractured zone under the crater, are much deeper and probably can be recovered only by shaft mining. Mining conditions might prove very difficult because of heavy ground in the fractured zone. Special support methods, including the filling of completed stopes,

- | | | |
|--------------------------|---|---|
| 1. BRINE PUMP | 4. PLANT FOR EVAPORATION,
CONDENSATION, AND MAKE-
BRINE CONTROL | 5. WATER STORAGE |
| 2. TUBING TO ICE HORIZON | | 6. WATER REMOVAL FOR ELECTROLYSIS |
| 3. RETURN TUBING | | 7. EXCESS SALTS AND OTHER SOLIDS
REMOVAL |

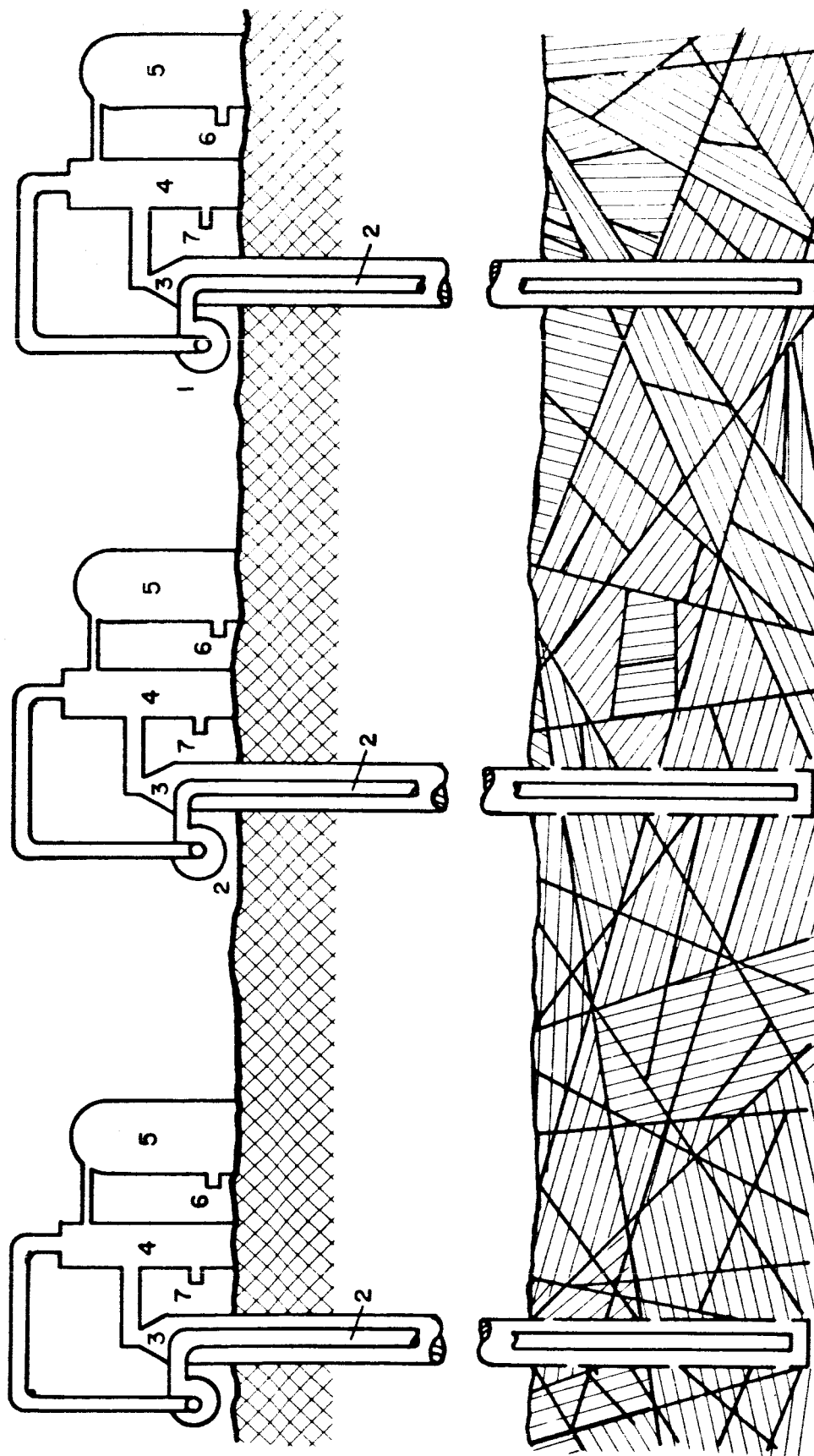


FIG. 16

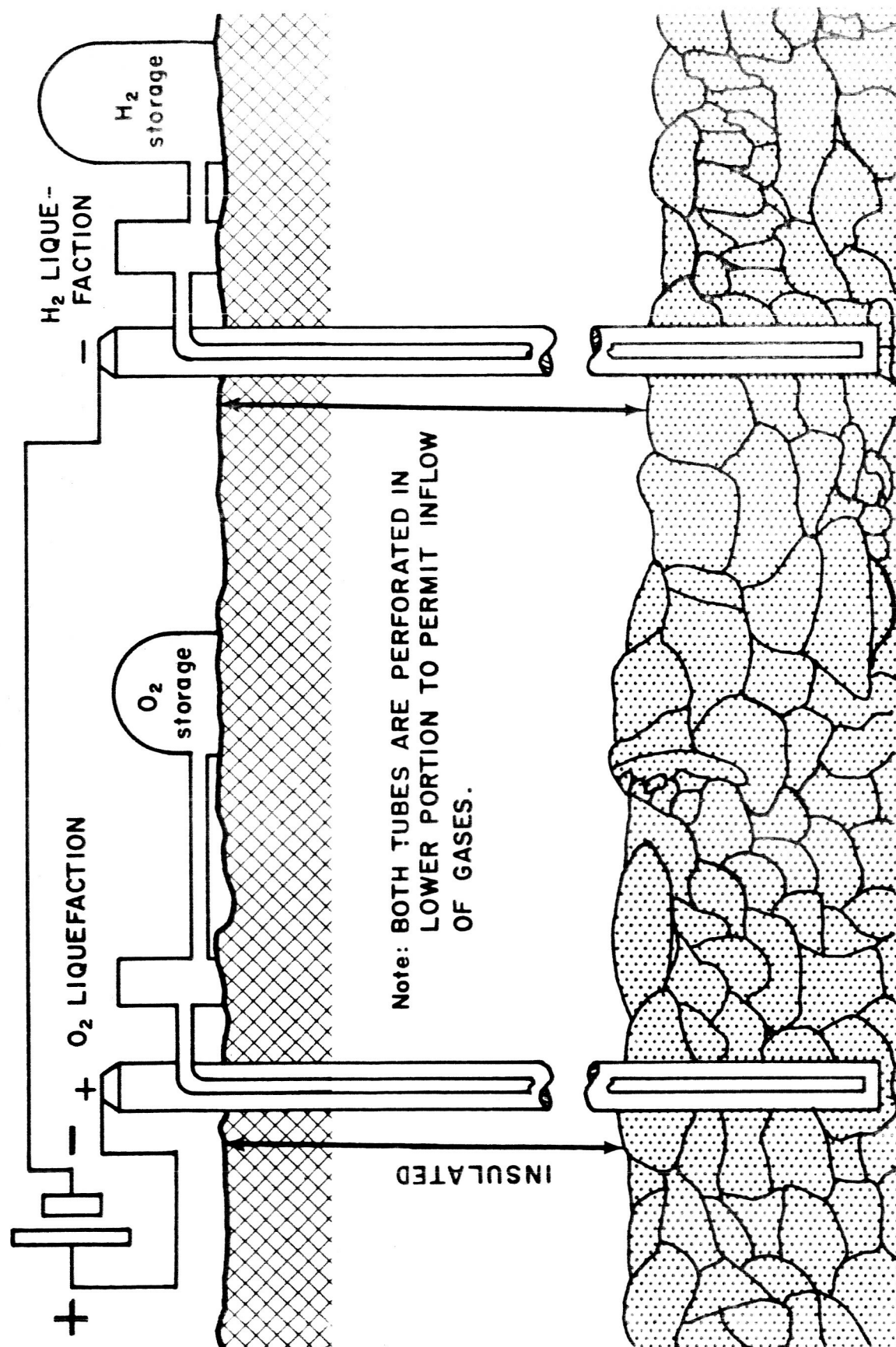


FIG. 17

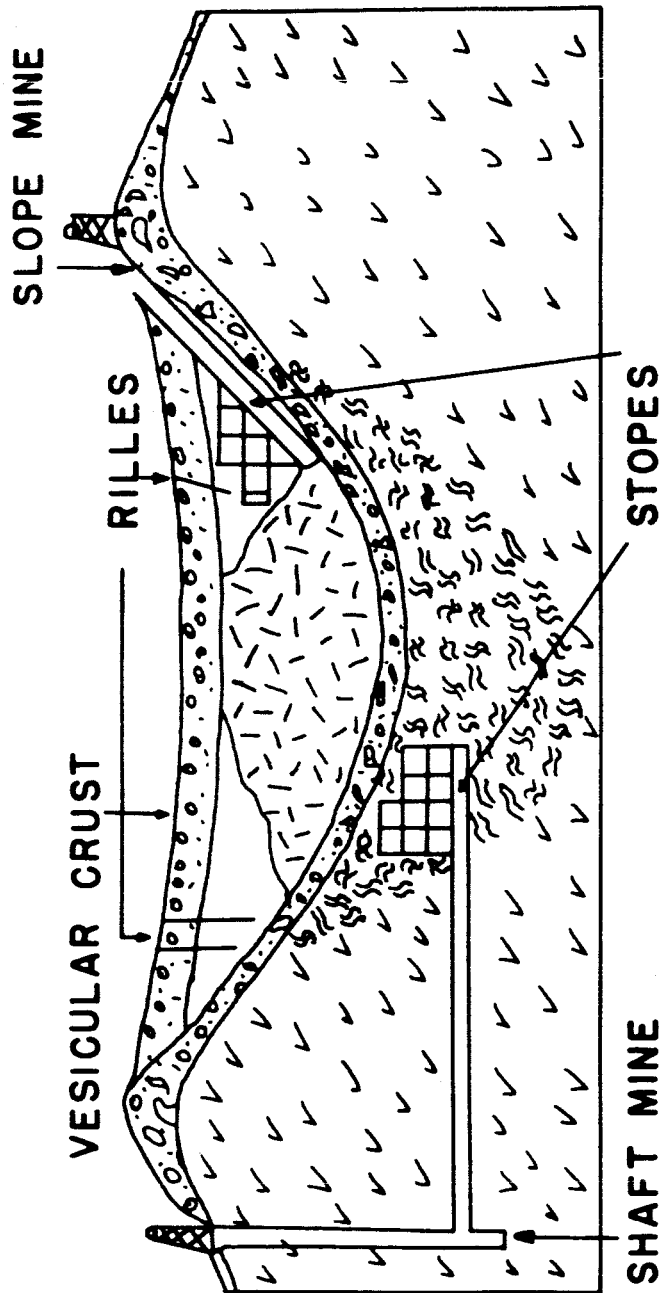
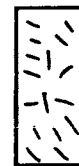
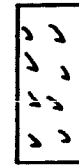


FIG. 18



CRYSTALLIZED
MINERALS



OLD HIGHLAND
MATERIAL

probably will be required. Neither of the mining systems of Fig. 18 is expected to be used until long after the initial lunar landing and after demand for water for base support and fuel becomes relatively great. These methods may never be used, if shallower and more advantageous deposits can supply the demand.

Fig. 18 may also represent another very sophisticated and fully automated mining system. The slope sunk to the ore zone on the crater margin, or even a much longer slope to the fractured zone under the crater, could be driven with a tunneling machine (Williamson, 1965). Once the ore is reached, it could also be mined with the same machine, much as development work is done in coal mining with continuous miners. Recovery would not be nearly as complete as with stoping but full automation and lower labor requirements should more than compensate lower recovery in large ore bodies. Support might be a problem in the fractured zone.

V

MODELS POSSIBLY SUITABLE FOR SURFACE MINING

In order that lunar ice or water-bearing minerals to be mined by strip or open cast methods, it is necessary that the deposits be fairly close to the surface. In the case of Frasch-type methods, however, mining from the surface can be done at any depth to which drilling is practicable. Mining by drilling will ultimately be limited by the ratio of thickness of overburden that must be removed and discarded to ore removed, and by the volume of ore needed. The overburden-ore thickness ratio cannot be set now, but 10:1 constitutes an estimate. This ratio means that a maximum of only 1/10 of total drilling time would produce ore, a very small proportion.

Large holes and thin overburden are necessary if any sizeable production is to be achieved with only one or two drills.

Auger mining from the surface will also require relatively shallow overburden but, if a fairly large auger is used, overburden need not be as shallow as that required by the exploration-type drill, either percussion or rotary. The latter drill is designed for penetration, not for volume removal.

Obviously, the more sophisticated tunneling machine and conventional underground mining methods will not be severely limited by depth. These two elaborate and expensive methods will, however, require larger sized, single ore bodies for economic operation, and a rather large ore production rate.

Strip mining of Model 1 deposits probably will be limited to shallowly flooded craters or to thin lava sections on the edge of the larger maria such as the "drowned" craters and small bays and inlets in southern Mare Nubium, south and east of the Straight Wall (Lunar Atlas photo D6-a, Kuiper, G. P., Ed., 1960) where the lava sheet is quite thin. The thickness of the vesicular layer overlying the

trapped volatile zone is also a factor in determining ore depth, but it is likely that micrometeoroid bombardment of this material has partly or completely reduced it to a mass of small, brittle, "glass" fragments forming a layer thinner than the originally expanded material.

Models 2 and 3 can be surface mined if one of the water-bearing permeable tuff layers is close enough to the surface as indicated in Fig. 14. Layers deeper than 10-20 meters must await a more sophisticated system like an indirect Frasch method or underground mining. If the maria are filled with lava flows rather than with tuff flows, the same restriction will govern mining method.

The impact highland crater, Model 4, probably cannot be surface mined. The thinnest rubble estimated by Salisbury and Smalley (1964) is 28m and that is in intercrater areas. The crater of Model 4 has a diameter of more than 20 km (13 mi) so that on the scale indicated in item 26, Table 2, the bottom rubble is at least 28m thick and probably more, and that on the rim must be much more than 83m thick. These dimensions probably will serve to eliminate surface methods. Small highland craters of under 100 m diameter, (Table 2), probably can be surface-mined right in the bottom but each will provide only a small ore body. The newest highland craters should have only a small thickness of rubble covering the bottom.

Model 5 may be mineable in some localities. The source of water in the permafrost zone is not clear from the model, but probably came from the fractured zone just under it.

The surface mining of rilles and chain craters (Models 6 and 7) will be most difficult. The immediate terrain is about as rough as is found on the maria and some rubble will have to be removed to reach ore. If ore is in the form of hydrous minerals, a large quantity of overburden probably must be removed. Strip mining

beginning on a hill is satisfactory, but if one must start in a "hole," as in these two models, there is likely to be too much "dead" work.

The sides of some of the larger rilles will be formidable obstacles to the movement of machinery. Baldwin (1963, Chap. 21) quotes Schmidt as saying that rilles are $1/3$ to $2 - 1/2$ miles wide, 20 - 100 miles long and 300 - 1300 feet deep, and states Fieldner as measuring depths of Adriadaeus rille of 1900 to 3800 feet near the middle. Undoubtedly, smaller rilles, telescopically invisible, exist. Perhaps in all rilles, places can be found where the sides have slumped and/or rubble has slidden into the rille, making a natural ramp to serve as an access roadway. Rille bottoms appear fairly level so that surface mining for shallow deposits might be done in the bottom, once it is reached.

Rubble embedded serpentine masses, Model 8, probably can best be mined by surface methods. The volume concentration of the serpentine boulders in the first 10-20 meters of highland surface will determine the practicability of mining such a deposit.

Surface mining lunar domes, Models 9 and 10, should not be difficult if the cover over the intruded mass is not thick. Even if thick originally, whatever erosive forces operate on the lunar surface should reduce the tops of "hills" more rapidly than the surrounding area. Westhusing and Crowe suggest Model 10 (their Model 4) may be a laccolith of ice or hydrous minerals (serpentine). Salisbury's model, No. 9, would only be serpentine. Either material would make a fine deposit but if Model 10 were a magma laccolith with only slight water enrichment or with water enrichment only around the margins, it would not be nearly as valuable.

Baldwin (1963, Chap. 23) says that lunar domes are 10-11 miles in diameter and a few hundred to a few thousand feet high. Thus, domes would constitute very large water or hydrous mineral deposits.

In spite of considerable height, domes have very gentle slopes. Even with thin or absent rubble cover, strip mining practice will be box-cut with no slopes steep enough for contour stripping.

If domes are shield volcanoes (many have craters in the center) neither Model 9 or 10, is valid.

Mining a mare rille which originated as a lava-intruded graben (Model 11), or a mare chain crater of similar origin, would face the same handicap as for Models 6 and 7: that of starting in the bottom of a hole or trench. Unless the intruded material were ice and other condensed volatiles or highly hydrated rock, these two models would constitute "lean" ore.

In summary, Models 1, 2, 3, 8, and possibly 9 and 10, are likely to be more suitable for surface mining than are the others. Even in these cases, depth of overburden probably will be the determining economic factor, once the deposit is discovered and proved.

VI

ENVIRONMENTAL PROBLEMS OF SURFACE MINING

The lunar environment is expected to prove harsh beyond anything encountered on the earth, including that of Antarctica. Personnel must be completely isolated from the environment at all times and equipment and installations will be required to withstand severe and rapidly changing conditions. Living quarters will have to approach close simulation of earth conditions and the close quarters, the isolation, the long day-night cycle and other factors, probably will make comparatively rapid rotation of personnel desirable.

At the distance of the moon from the earth, all lunar environmental conditions are not determinable and measurements of some others are doubtful or contradictory. There appears to be, however, increasing agreement on the part of investigators as to the magnitude of many factors and the existence or non-existence of others. Table 2 was compiled to show probable values of a number of determined or estimated environmental factors, and estimated ranges for others. Some of the important environmental factors that will affect surface mining operations directly, are as follows:

(1) The lunar day-night cycle. It may be found undesirable to conduct surface mining operations during the almost 14-day light period. If the ore is free water, exposure to day-time temperatures will result in rapid evaporation. If mining is done in the dark, an ore exposure cannot be left during the light period but will have to be shielded. Hydrous minerals would not be so affected, unless it be those containing rather loosely bound molecular water.

TABLE 2

Most Probable Value and Ranges of Certain Lunar Environmental Factors

LUNAR ENVIRONMENTAL FACTORS	POSSIBLE RANGE	PROBABLE FACTOR	REFERENCES
1. Atmospheric Pressure	1.033×10^{-6} to 10^{-8} Newtons/m ²	1.033×10^{-8} Newton/m ²	Elsmore, 1957
2. Atmospheric Composition	Ne, Kr, Xe, CO ₂ , H ₂ , H ₂ O	Kr, Xe, ionized	Salisbury, et al, 1965
3. Temperature, surface, max., near 0° lat.	390-410°K	407°K (134°C)	Sinton, 1962
4. Temperature, surface, min., near 0° lat.	104-122°K	105°K (-168°C)	Salisbury, et al, 1965
5. Temperature, subsurface, depth > 1 m (?)	-23°C to -53°C	233°K (-40°C)	Salisbury, et al, 1965
6. Gravitational Acceleration		1.60 m/sec	Salisbury, et al, 1965
7. Meteoroid flux (particles > 1 gm)		8.78×10^{-14} particles/m ² /8 hrs. (1) McCracken & Dubin, 1964	
8. Micrometeoroid flux (particles 10 u radius)		$8.78 \times 10^{-1.7}$ particles/m ² /8 hrs. (1) McCracken & Dubin, 1964	
9. Solar Wind - ave. proton flux		2×10^{10} /m ² sec	Wehner, 1964
10. Solar Wind - ave. α - particle flux		0.3×10^{12} /m ² sec	Wehner, 1964
11. Solar Storm - proton flux		2×10^{13} /m ² sec	Wehner, 1964
12. Solar Storm - α - particle flux		3×10^{12} /m ² sec	Wehner, 1964
13. Sputtering rate - max., solar wind, protons + α - particle		0.34 Å/yr. (Stony materials)	Wehner, 1964
14. Magnetic field, max.		30 gammas (3×10^{-4} gauss)	Salisbury, et al, 1965
15. Surface electrical charge		+20 volts	Opik & Singer, 1960
16. Dielectric constant, lunar surface	1.1-2.7	~ 2	McCracken & Dubin, 1965
17. Vacuum adhesion, fine silicates		75 Newton/m ² (750 dynes/cm ²)	Salisbury & Smalley, 1964
18. Density, underdense surface reflecting layer		500 kg/m ³	Est., Jan. Proj. Rept., NAS8-20134
19. Density, rubble, maria		1900 kg/m ³	Estimated
20. Density, rubble, highland		1700 kg/m ³	Est., Jan. Proj. Rept., NAS8-20134
21. Density, "solid" lunar rock	2700-3250 kg/m ³	3250 kg/m ³	Estimated
22. Thickness, underdense surface layer, ave.	0.1-1.0 m	< 1 m (2)	McCracken & Dubin, 1964
23. Thickness, intercrater area, maria, ave.		0.6 m	Salisbury & Smalley, 1964
24. Thickness, intercrater area, highland, ave.		28 m	Salisbury & Smalley, 1964
25. Thickness, rubble near 100 m crater, maria		15 m	Salisbury & Smalley, 1964
26. Thickness, rubble near 100 m crater, highland		83 m	Salisbury & Smalley, 1964
27. Chemical composition, maria rubble	granite-peridotite	basalt	Estimated
28. Chemical composition, highland rubble	granite-peridotite	granodiorite	Westhusing & Crowe, 1964
29. Chemical composition, maria rock	granite-peridotite	basalt	Westhusing & Crowe, 1964
30. Chemical composition, highland rock	granite-peridotite	granodiorite	Westhusing & Crowe, 1964
31. Thermal inertia, underdense surface layer, $(kc\rho)^{-1/2}$ cm ² - sec ^{1/2} °C/cal		140	Weil (1965)
32. Thermal inertia, homogeneous lunar surface, $(kc\rho)^{-1/2}$ cm ² - sec ^{1/2} °C/cal		435	Weil (1965)
33. Thermal inertia, mineral foams (perlite), $(kc\rho)^{-1/2}$ cm ² - sec ^{1/2} °C/cal	100-540	510	Glaser, et al (1965)
34. Thermal inertia, mineral powders (basalt), $(kc\rho)^{-1/2}$ cm ² - sec ^{1/2} °C/cal	630-3300	870	Glaser, et al (1965)
35. Thermal conductivity, sintered perlite (cal/cm - sec °C)		5.9×10^{-5}	Glaser, et al (1965)
36. Thermal conductivity, powd. olivine basalt, (cal/cm - sec °C)		4.0×10^{-6}	Glaser, et al (1965)

(1) Assumed density, 1 gm/cm³

(2) Jaffe (1966) concludes there may be a dust layer up to 5 m deep on Mare Cognitum.

Advantages of night-time operations will be: (a) uniform (if low) temperature conditions, (b) uniform lighting from the earth, as earth-shine, or none, (c) absence of solar wind, (d) possible absence or reduction of rarefied ionized gases of the thin lunar atmosphere, (e) possible absence or reduction of a postulated surface electric charge (item 15, Table 2), (f) no cooling needed for space suits and/or machine cabs or structures, and (g) better heat dissipation from bearings, motors, etc.

Possible disadvantages of night operation are: (1) the necessity to provide artificial lighting, at least part of the time, (2) the high heating load for space suits, cabs, and structures, (objectionable only if primary power is solar and battery storage is required for night operation), and (3) the increase in freezing of working fluids, if any are used.

If it proves practicable, a thin aluminum or plastic (if stable in solar radiation) awning over the entire operation, or at least over personnel and equipment, will simulate night conditions because there is no atmosphere to scatter and diffuse light or other radiation.

(2) The wide temperature range. Table 2 indicates the wide range of day-night temperatures. Results from lunar eclipse measurements indicate that light-shadow temperature contrasts in lunar daylight can be almost as large and temperature changes extremely rapid. Changes up to $174^{\circ}\text{K}/\text{min.}$ have been observed (Sinton, 1962) and on metal this might exceed $200^{\circ}\text{K}/\text{min.}$ In daylight, parts of a working machine would be alternately exposed and in the shadow of other parts so that large and rapid temperature stresses may be induced. A straight aluminum rod, half in the sun and half in its own shadow, if a meter long on the underside would be about 1.0375 meters long on top. This should tend to warp and shorten the rod appreciably and set up large temperature stresses. Shielding the rod from radiation would, of course, reduce the ambient temperature on both sides to a low

but near uniform figure. Radiation reflected from surrounding lunar surfaces might provide some heat and light under the shielding canopy, but the general lunar albedo is so low that, in the case of light, the intensity would be no more than 5-10 percent of that falling on the reflecting surfaces.

Equipment design and construction must take the temperature and temperature change factor into consideration.

(3) Low Pressure Lunar Atmosphere. If the lunar atmospheric has the maximum value shown in item 1, Table 2, it would be rated a hard vacuum on earth. At such pressures, lubricated bearings must be sealed or solid lubricants like graphite or MoS₂ used. Even solid greases would evaporate rapidly. The combination of low atmospheric pressure, low and high temperatures, rapid temperature changes and no convective cooling (unless built in), will pose some real lubrication problems in design of high-speed equipment for lunar use.

The lunar atmosphere is so rare that it is no factor. There will be no atmospheric oxidation or other chemical effects. If the atmosphere consists of a low temperature plasma of charged Ar and Kr ions, the condition might result in a little electrical charge leakage under some circumstances, but the effect should be small. At earth atmospheric pressure, Ar⁺ would be present at a concentration of 2.59×10^{19} ions per cubic centimeter; at lunar atmospheric pressure (maximum possible), this would be only 2.59×10^6 ions/cm³.

The lunar atmosphere gives no shielding from solar radiation or from micrometeoroids.

(4) Meteoroid and Micrometeoroid Bombardment: Ever since lunar landings have been considered a possibility, the question of the possible danger to personnel on the lunar surface and the problem of protection from impacting cosmic material, in case it proves a great danger, has been considered important. Apparently the

danger of impacts to space travel in the vicinity of the earth, where the micro-meteoroid flux probably is greater than in the space around the moon, has not proved as great as many at first feared it would be. If the flux rates shown in Table 2 are correct, the danger to man should be small. One m^2 is larger than the exposure surface of an upright man on the lunar surface and the earth work-day length was chosen rather arbitrarily as the maximum length of a single period of exposure time. The figures suggest that only one particle, weighing one gram or more, will strike a given square meter of surface each 8 hours once in 8.78×10^{14} 8-hour periods or $\sim 3 \times 10^{14}$ earth days. The chances of hitting a man of $< 1 m^2$ cross section are even lower than once in 3×10^{14} days ($\sim 8.2 \times 10^{11}$ yrs.).

A particle, however, does not have to weigh a gram to damage a man in a space suit. Velocities may vary from 10-72 km/sec (72 km/sec, escape velocity from solar system, Weil, 1965), with most particles striking the moon at 10-20 km/sec (20 km/sec escape velocity from earth-moon system). McCracken and Dubin (1964), suggest 10 km/sec for dust particles with micron dimensions. Item 8, Table 2, 10 micron diameter or \sim 800 Tyler mesh was rather arbitrarily chosen as perhaps the largest particle that would do no damage. The particle may, however, be too large to be harmless. Using McCracken and Dubin's (1964) value of 10 km/sec (10^6 cm/sec) for velocity and a density of 1.0 gm/cm^3 , a 20 micron diameter ($r = 10u$) particle has a mass of 4.2×10^{-9} grams and a cross sectional area of $3.1 \times 10^{-6} \text{ cm}^2$. Its kinetic energy is 2.1×10^3 dynes but the unit pressure exerted is $6.8 \times 10^8 \text{ dynes/cm}^2$ ($6.8 \times 10^7 \text{ Newton/m}^2$). This is equivalent to 9.86×10^3 or 9860 lb/in² (which is quite a wallop for so small a particle).

The next larger particle ($r = 100u$ or about 65 Tyler mesh) would exert an impact unit pressure ten times as great or 98,500 lb/in². The smallest dangerous

particle probably lies between these two sizes. Fig. 19 is an "average" curve, modified from McCracken and Dubin in terms of number of particles/ $\text{m}^2/8$ hours; the flux of any sized particle considered safe can be picked from the graph.

(5) The Solar Wind. The ultraviolet radiation on the lunar surface, unimpeded by an atmosphere, is much more intense than on earth. In addition, the protons and α -particles of the solar wind, which are repulsed or slowed by our magnetic field and atmosphere, beat full force on the lunar surface. Measures for the adequate protection of personnel from the lunar vacuum should also be sufficient for protection from the solar wind. Protection of equipment and structures from sputtering has been a lively problem but, if the value shown in Table 2 is correct even by one order of magnitude, the problem at most should be a very long term one only and probably will not exist as a practical one for metals or ceramics.

(6) Gravitational Acceleration: The strength of the moon's gravitational field, including the acceleration at the surface, is well known. As on the earth, however, the field may vary slightly, both latitudinally and locally. The moon rotates too slowly for appreciable polar flattening, but there may be some. There is proof that a lunar "bulge" is directed toward the earth which should result in a lower than average acceleration on the bulge (farther from the center) unless compensated for by denser material in the bulge. Salisbury, et al, (1965), concludes that lunar gravitational acceleration varies with latitude and longitude up to possibly 1 part in 8000. Variations with topography are estimated as about 1 part in 7000.

Gravity may also vary with internal density. To explain apparent anomalies in the three lunar moments of inertia, it has been suggested that variations in density may occur in the lunar interior (Urey, et al, 1959). In a recent, very

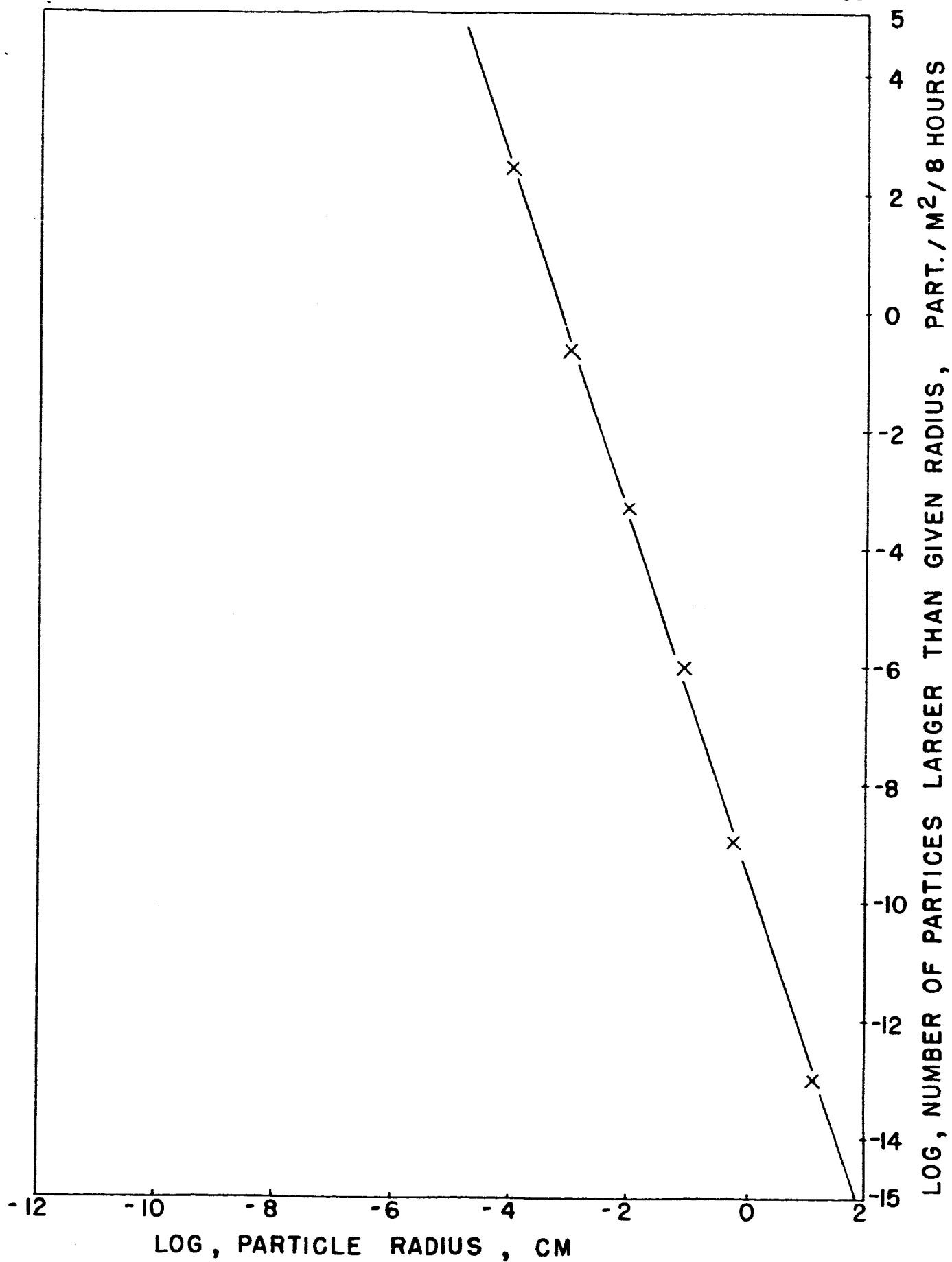


FIGURE 19

thorough, review, Lamar and McGann (1966) were unable to produce a lunar model consistent with all the data. The lunar gravitational field may, therefore, be more complex and variable than that of the earth.

(7) Magnetic Field. No lunar magnetic field has been detected and the value given in Table 2 is a probable upper limit. If there is no field, or a weak one, there should be no effect on mining operations, either beneficial or adverse. If there is a weak field, it should not extend far from the moon on the sun-lit side because of the effect of the solar wind on the magnetopause (Ness, 1966), nor could it have a very long tail on the dark side. There may, however, be local magnetic fields, if the moon has appreciable meteoritic nickel-iron masses buried near the surface (Shotts, et al, 1963). These masses may have been magnetized by passage through one or more magnetic fields in space or through the "tail" of the earth's field (Ness, 1966). If meteorites impacted the lunar surface with enough energy to vaporize, melt, or even attain temperatures above the curie point as a solid, they may become demagnetized. This appears unlikely, certainly for some of the lower velocity objects.

(8) Dielectric Constant. It is not clear what effect, if any, the low dielectric constant of the lunar surface, determined from radar studies, will have on the mining environment. Salisbury and Smalley say (1964): "These values of dielectric constant (ranging between 1.1 and 2.7) are lower than for ordinary terrestrial rocks, thereby indicating a surface material of low bulk density and of a depth between a few centimeters and 10 meters." This is a wide depth range, in excess of a 1:100.

(9) Surface Electrical Charge. A positive surface electric charge evidently is postulated because of the displacement of electrons by solar wind bombardment. There should be little effect on mining unless more careful grounding or insulation of electrical equipment is required than on earth.

(10) Vacuum Adhesion. The extent of vacuum adhesion is one of the great unanswered questions regarding the lunar surface. Virtually all high vacuum experimental work has demonstrated the presence of adhesion among small silicate particles and between these and some surfaces (Fields, 1966; Halajian, 1962; Ryan, 1965) but none conclusively prove that in the harder lunar vacuum, dust or larger particles, will settle on and coat surfaces, build up on wheels or tractor treads, or render digging of dust or fine rubble difficult. It is probable that there will be no final answer until a moon landing is made. If vacuum adhesion is a serious problem in lunar mining it may be so only for the first meter, or less, or material. At greater depths, there may be enough water or other condensed volatiles of sufficient vapor pressure for coating nearby or newly created surfaces with vapor so as to prevent the "ultraclean" condition that may exist at the lunar surface and thus prevent very much adhesion, even for small particles. An ore containing even traces of free water should not be stubbornly adherent.

(11) Dust and Rubble Densities. If underdense lunar surface material has a density of 0.5 gm/cm^3 or 500 kg/m^3 , this corresponds to a porosity of 80 percent. Halajian (1965) discusses porosity and gives estimates ranging from 50 percent to 90 percent. He favors a bulk density of 0.4 gm/cm^3 which is a porosity of 84 percent. These values are, therefore, somewhat speculative although the lunar surface photometric properties apparently do require underdense material.

The bulk density of dry sand and gravel is variable, depending heavily upon the particle size distribution but usually runs 105-115 pounds/ft³. The theoretical maximum bulk density for closely packed silica spheres of uniform size is about 120 pounds/ft³. The value chosen for highland material is about 106 pound/ft³ or 1700 kg/m^3 . The higher value for maria rubble (1900 kg/m^3) is based on the assumption that maria rock may be more basic (or contain more iron) than

highland rock. These two values can vary somewhat, depending on particle shape, degree of compaction, and composition.

Density of "solid lunar rock" is essentially in the range from highly quartzitic to highly basic rocks on earth. A value of 2720 kg/m^3 is about right for granodiorite (Spock, 1953).

(12) Rubble Thickness. The rubble thickness estimates from Salisbury and Smalley (1964) were the only ones found in the literature. Undoubtedly they are estimates based upon crater size and frequency, height of crater rims, etc. Weil (1965) sees the maria as covered by rock, presumably solid from cooling lava, with a 1-3 cm dust mantle overlying it. He suggests that "intact rock" may not be encountered except at depths of about 1 km below the surface.

(13) Chemical Composition of Lunar Rubble and Rock. Loomis (1965) gives a most complete discussion of possible lunar rock types but does not suggest a preference. Westhusing & Crowe (1965), in their models, show volcanic tuff or basalt as the material filling the maria, and granodiorite as the "original rock" of the highland areas. We are inclined to pick a compromise composition a little farther toward a basic composition (Shotts, 1966), possibly gabbro or anorthosite; but, if there is any differentiation at all in the lunar crust, granodiorite probably is a good choice for the crustal zone.

(14) Thermal Properties. Studies of the rate of change in temperature of lunar surface during the lunation cycle and during eclipses enables us to calculate the "thermal inertia" of the surface layer, $(k\rho c)^{1/2}$. Thermal inertia is the reciprocal of the square root of the product of thermal conductivity, k ; density, ρ and specific heat, c . If two of these factors could be fixed, the other one would be also.

The first values given by Weil (1964) is for a very fine powder, 2.5 m thick (dust layer), and the second is " - - - for (the) homogeneous moon as a whole - - - ". Weil states that the thermal inertia of rock is ~ 20 and " - - - 1,000 for very fine dust under simulated lunar conditions. " Two layer models consisting of fine dust over coarser materials and a surface of 95 percent dust and 5 percent bare rock, have been suggested. Glaser, et al (1965), quote Krotikov and Troitskii as estimating that a one-layer model in which $(kpc)^{-1/2} = 350 + 70$, is satisfactory. They further postulate underdense material of 0.5 gm/cm^3 density down to at least one meter depth. If specific heat is about 0.2 cal/gm , k becomes $\sim 10^{-4} \text{ cal/cm-sec-}^\circ\text{k}$. Table 2 shows neither mineral foam (sintered perlite) nor mineral powder (olivine basalt), are within the lunar $(kpc)^{-1/2}$ limits. The thermal conductivities of items 35 and 36, Table 2, are also one order smaller than those calculated from the work of Krotikov and Troitskii. Apparently, it will be necessary to collect data on thermal properties of what are believed to represent most likely lunar materials and base plans and designs on the entire possible range of values.

(15) Another possible lunar condition, based upon no measurements, is that corrosive gases, vapors, etc. may be encountered beneath the lunar surface. If the moon were melted early in its history, it might be almost completely devolatilized. If heating came later (from radioactivity or from tidal friction), the moon should be only partly devolatilized and many condensible vapors like F_2 , Cl_2 , HCl , HF , SO_2 , H_2S , etc. may be entrapped in the outer crust. In the case of lunar cold accretional origin, the concentration of condensible vapors (including water) in the outer layers may be low unless they have been driven toward the outside (Shotts, et al, 1963) by internal heating in a moon of chondritic composition (MacDonald, 1961). In case corrosive conditions are encountered, designs of machines for

digging, loading, drilling and other uses must incorporate corrosion-resistant materials, and mining and processing system designs must protect personnel and equipment against corrosive and harmful substances.

(16) General Structure of the Upper Surface. Weil (1964) gives an excellent summary of the structure of the moon and of its surface to a depth of about one kilometer. It generally agrees with the ideas presented by Salisbury and Smalley (1964). He states:

"The maria are expected to consist of solid rock resulting from the cooling of lava flows, overlain by a thin dust mantle 1-3 cm thick. This dust mantle, partially the result of micrometeorite infall, partly the result of thermal fracturing, is very fluffy in appearance with a void ratio possibly as high as 75 percent. The generally featureless flat appearance of the maria is periodically interrupted by isolated craters which, however, comprise no more than some 3 percent of their surface area. Around these craters the normal debris of ejecta and brecciated material will be found, stretching out in a gradually thinning fashion to a distance of about four crater diameters from the impact locus.

The highlands will entail totally different conditions. The subsurface stratifications are extensively brecciated in this region, so that intact rock may not be encountered to a depth of about 1 km beneath the surface. Only the tops of crater rims, large boulders, and very steep crater slopes are free of dust; in these limited areas bare rock is likely to be encountered, which is very slowly being eroded away

under the action of micrometeoritic impact and thermal exfoliation.

The inner and outer crater slopes are covered with dust which becomes increasingly thicker as the slope becomes milder. The dust might be in precarious balance on some of the steeper slopes, and is slowly migrating downhill under the influence of the levitation transport mechanism. "

In addition, he makes these points:

1) Salisbury's estimate of a maximum size of rubble block of 4.5 meters from a crater of 100 meters diameter, is possibly too high. Larger blocks are gradually buried under dust (from thermal fracturing and micrometeoritic infall).

2) Micrometeorites (lower limiting size, 0.83 microns owing to Poynting-Robertson effect) tend to generate a powder, 1 to 100 microns in size. The mean should be ~ 6 microns and the distribution is skewed toward the smaller particle end. Dust due to thermal exfoliation cannot be extremely fine but should be fairly uniform with a maximum particle size of 100 microns.

"The particle spectral distribution of this lunar dust is likely to vary over a broad range (1 micron to 1 meter) - - -. The mean particle size - - - should not be expected to be much above 10 microns and - - - arranged in intricate 'fairy-castle' structure of a very big porosity (to 75 percent) with a - - - low bearing strength. "

3) Basins of lunar craters are probably filled with dust up to several km thick. "The bottom layers, therefore, are strongly compacted by the overburden, lack electrostatic charges and may be cemented by moisture frozen into ice at the prevalent low temperature. - - - Proceeding upward from the bottom of crater dust beds, density and apparent cohesion drop until one arrives at the surface where the same porosity and fluffy consistancy is expected - - -."

4) The powder surfaces are charged positively to about 20-25 volts.

5) Ranger VII photos show "the ground in the maria is gently undulating. Round craters - - - exist in sizes down to resolution limit - - - and appear to occupy some 5 percent of the ground - - - . There are a few sharp edged, small craters. - - - The picture creates the impression of a generally featureless terrain - - - ."

VII

TWO SHORT STUDIES OF SPECIAL PROBLEMS IN LUNAR MINING

A. Transportation and Handling of
Lunar Mineral Substances and Derivatives

Lunar Environment: In the design of lunar systems for transportation of ores, minerals, and their products, basic assumptions must be made concerning environmental factors and physical conditions which limit the capabilities of each system and hence control the choice of applicable transportation media. This report will seek to establish a range of values for these factors and to propose models of systems which will be operational under conditions of an adverse environment.

The consensus of the numerous workers involved in lunar environmental studies indicates the values set forth below more probably will prevail. *

1. Surface temperatures at 0° latitude will range from a maximum of 407°K (134°C) to a minimum of 105°K (-168°C). Temperature of the subsurface at a depth of 2 meters or more will remain fairly constant at about 233°K (-40°C).

Surface temperature extremes would result in expansion and contraction stresses beyond the yield limits of common metals and alloys. In the case of pipelines as a transportation medium, therefore, it would be necessary to (a) bury pipelines below the surface, (b) shield the lines if same are placed on the surface, or (c) utilize flexible synthetic materials which will withstand the stresses imposed at the surface.

2. Lunar surface material consists of low-density, porous rubble, pulverized rock, and dust comprising a more or less uniform layer ranging up to 15 meters thick of low thermal conductivity, low relief, accreted to a certain degree

* Data were compiled from many of the authorities cited in the list of references appended to this report. See Table 2.

by vacuum adhesion, with a bearing strength in excess of 750 dynes/cm^2 at the surface increasing rapidly with depth.

Surface material and conditions are then such that (a) permit burial of pipelines to a depth of 1 to 1.5 meters by use of a common-type ditching machine or similar device, (b) provide insulation to maintain a constant temperature at shallow burial depth, and (c) afford adequate bearing strength for all structures critical to transportation systems.

3. Atmospheric pressure at the Moon's surface is probably as low as $1.033 \times 10^{-8} \text{ Newtons/m}^2$.

It is assumed the effects of a virtual vacuum will not alter the operational performance of equipment nor affect appreciably the critical constants or phase relationships of liquid, vapor, or solid mineral or manufactured substances.

4. Meteoroid flux of particle size sufficient to damage materials and equipment is assumed to be operative.

In certain instances, protection from impact of foreign bodies will be required.

5. Sputtering effects, solar bombardment, vacuum adhesion, and other potential adverse environmental factors are not of significant proportions as relate to transportation systems and operations.

Transportation and Handling: Transporting fragmented ore from one fixed point to another (e. g. mine to processing plant) may be accomplished by continuous-flow methods or batch methods. A system planned for continuous flow has the advantage of low-capacity equipment coupled with low and constant power requirements, resulting in low operating and maintenance costs. In addition, storage (or surge-bin), facilities are held to a minimum. Pre-fabricated sections of continuous-flow equipment can be conveniently handled and erected. Such equipment used on earth

consists of conveyors (belt, shaker, flight), aerial trams, and pipelines. These systems permit a high degree of automation. It may be noted that shaker conveyors should operate at high efficiency under low-gravity conditions. Both belt and shaker conveyors, however, are applicable only where the terrain is relatively moderate. Flight conveyors can be used under more rugged conditions.

Where a higher degree of flexibility is required because of small scattered ore deposits, need for blending, etc., surface batch haulage will be preferable. This requires self-propelled vehicles which may be of the skid, wheel, or walking type. Choice would depend upon degree of roughness of the terrain. Skid and wheel type would require graded roadways; the low order of gravitational effects will require that curves be of exceptionally long radius.

In the following paragraphs, the methods of transporting ore and mineral products which appear feasible and applicable to lunar operations are discussed. The discussion will be in outline form for the sake of brevity.

Transfer of Raw Ore to Processing Plant

A. Fluo-solid method: The transfer of ore or mineral substances from the mine to the processing plant will require a closed system such as a pipeline if the raw ore should be in the initial form of a solid such as a pumice-like silicate impregnated with permafrost which might either sublimate or liquify if subjected to surface or near-surface temperature conditions. A pipeline (a) buried at a depth of less than 2 meters or (b) laid upon the surface but shielded from direct and reflected rays of the sun might provide an approximately constant temperature of suitable range of value.

Depth of burial possibly would afford a choice of temperature of the range of 173°K to 233°K (-100°C to -40°C) which in turn would afford a choice of propellant in a fluo-solid system. It is further conceivable that a surface line might be

(a) shielded or (b) insulated to an extent that would provide a temperature of the range of liquidity of water (or another propellant) during the 14-day period of lunar sunlight.

Propellants: Propellants required in a closed fluo-solid system may be in either liquid or gaseous phase; the phase selected will depend upon a combination of conditions of temperature, availability, nature of the ore, pipeline properties, economic considerations, and human factors involved.

It is assumed the propellant employed will be available on the Moon in either the natural or the manufactured state at a cost competitive with imported substances. The propellant may be a product of the mining operation it is intended to serve.

Three models are proposed employing propellants which should remain in the liquid or vapor phase at anticipated surface or near-surface temperatures and of which one or more may probably be available from lunar sources.

1. Model A: Water

Operating temperature range of $\pm 1^{\circ}\text{C}$ to 99°C required for liquid phase; possibly attained by (a) burial of pipeline at shallow depth, (b) heating buried line, (c) insulating surface line, or (d) shielding surface line from sun's direct rays and employing reflected rays to provide temperature required. * Conditions (c) and (d) would result in operating conditions only during the 14-day sunlight period each lunar month which would involve stockpiling at the mine the ore produced during the balance of the month.

Vapor phase as propellant requires temperature greater than 100°C , attained by surface pipeline during sunlight period. Liquid water at source fed into

* Temperature ranges used herein do not take into account the absence of an atmospheric pressure.

high-temperature line would, upon flash vaporization and expansion, supplement or provide total of required transmission power.

Advantages of water as propellant: (a) availability; the singular substance more likely to occur in the natural state or as manufactured product; (b) chemically non-reactive with common ores; (c) non-corrosive with respect to pipeline material; (d) easily recovered and cycled; (e) biologically inert, non-toxic for human handling.

2. Model B: Chlorine

Operating temperature range of $\pm -104^{\circ}\text{C}$ to -33°C required for liquid phase; temperature possibly attained by burial of pipeline to depth of 1 to 2 meters.

Gaseous phase operating temperature greater than $\pm -34^{\circ}\text{C}$; attained by pipeline burial at shallow depth or by surface pipeline during sunlight period.

Advantage of chlorine as propellant: (a) availability; possibly occurs (1) in natural state as gas emanating from vents or as gas or liquid in drilled wells or (2) as product manufactured from chlorides or other compounds; (b) temperature of the lunar near-surface (+1 meter) and surface compatible with critical constants of chlorine; (c) liquid phase would provide operation 28 days per lunar month.

Disadvantages of chlorine as propellant: (a) in either liquid or gaseous phase is corrosive to many materials; (b) chlorine probably is chemically reactive with most potential ores; (c) toxic and dangerous for human handling.

3. Model C: Acetylene Gas

Operating temperature greater than $\pm -84^{\circ}\text{C}$; attained by burial at shallow depth or as surface line.

Advantages of acetylene as propellant: (a) availability; possibly occurs (1) in natural state as emanation from vents or from drilled wells or (2) as product manufactured from carbides or other compounds; (b) non-corrosive to most

common materials; (c) non-reactive chemically with common ores; (d) boiling point temperature suitable for pipeline buried at shallow depth thereby providing uninterrupted operation 28 days per lunar month; (e) easily recovered; (f) moderately safe for human handling.

Recovery and cycling of propellant: It is presumed the particular propellant employed would be recovered and returned to the point of origin for re-use.

1. If liquid water or liquid chlorine were employed, the propellant would be recovered by centrifuge or gravity separation, filtered if required, and returned to the source in liquid form by (a) return line parallel to the transmission line or (b) reversing flow of transmission line.

2. Water in the vapor form would be condensed and returned as liquid by a return line under operating temperatures of liquid water.

3. If chlorine gas were employed, the propellant would be returned in gaseous form by means of a parallel line or reverse flow of the transmission line.

Nature and properties of pipeline: Pipelines may be classified as two broad categories resulting from the nature of the pipeline material. One such classification would have as a basis whether the material is rigid or flexible, and consideration of this property is critical to planning lunar systems because of physical problems associated with terrain, temperature extremes, and meteoroid impact.

1. **Rigid material:** Nominally considered to be an alloy of aluminum, magnesium, or other lightweight metal, or a synthetic which may be referred to as a "plastic."

Desirable properties include: (a) light weight; (b) moderate to high compressive and tensile strength and burst and collapse resistance; (c) resistant to chemical corrosion; (d) resistant to abrasion from solids transmission and to

meteoroid impact; (e) low coefficient of thermal expansion; (f) simple coupling design; (g) easily salvaged; (h) "permanent" installation.

Disadvantages usually associated with rigid tubing: (a) metals have excessive thermal expansion and contraction; (b) metals subject to chemical corrosion from fluids transported and from potential corrosive fluids of a subsurface environment; (c) subject to damage in handling; (d) couplings generally complicated; (e) will not conform readily to rough surface terrain; (f) requires ditch of consistent grade when buried; (g) weight excessive if meets strength requirements.

2. Flexible material: Generally considered to be synthetics of the nature of (a) petrochemical derivatives or (b) rubber-impregnated wire or nylon/rayon mesh.

Desirable properties: (a) light-weight material; (b) chemically inactive; (c) flexible, affected very little by temperature extremes; (d) resistant to rupture; (e) simple coupling design, either friction clamps or chemical "welding"; (f) easily transported in coils of considerable length; (g) conforms readily to rough terrain or irregular ditch; (h) resistant to meteoroid impact; (i) little maintenance required.

Disadvantages usually associated with flexible tubing: (a) may not withstand rapid temperature change; (b) low collapse resistance; (c) low pressure rating; (d) may be chemically unstable; (e) subject to damage by other surface activities if not buried.

B. Solids transfer: The transfer of solid raw ore or mineral material will be considered on the basis of (a) distance from the mine to the processing plant and (b) surface topography and roughness.

Arbitrary values for distance will be adopted, and topographic relief and roughness will be defined in only general terms.

1. An overhead aerial-tram or cable-car system is proposed for long hauls and for shorter distances if the terrain is rough. A long haul will arbitrarily be considered as one of 1000 meters or more, or of the range of 500 meters if vertical elements of the topography are of the range of 5 meters or more.

A cable-car system would consist of supporting elements of tubular construction fitted with bearing plates adjustable in a vertical sense to conform to a rough terrain, and a continuous cable to which gondolas or bottom-opening cars would be attached. The cable would be powered electrically, and would be provided with gravity idler pulleys to accommodate sag and stretch and contraction with temperature changes. The cars would be loaded by remote control at the mine and unloaded by automatic dumping mechanism at the processing plant; no hand operation would be involved.

Advantages of an overhead cable-car system: (a) system is flexible, portable, easily installed, removed, lengthened or shortened; (b) rough terrain is no problem; (c) not affected by temperature extremes; (d) meteoroid bombardment and solar wind are not factors; (e) system is mechanically simple, easily automated; (f) will accommodate rock particles of any size; (g) requires no auxiliary equipment for installation.

2. A belt conveyor system is proposed for short hauls. A conventional system employed in mining operations would be readily adaptable to lunar mining where the topography permits. This method of transporting raw ore would afford the same operational advantages as the cable-car system except the utility in any terrain.

Transfer of Spent Rock from Processing Plant

A. Solids transfer: It is assumed the processing plant will be so located that spent rock may be disposed of in the immediate area. Two systems for disposal of waste are outlined below.

1. Belt conveyor: This system is proposed for solids transfer where short distances are involved. Its operational advantages are evident; it is not affected adversely by lunar environmental extremes.

2. Pipeline: Pipeline transportation of spent rock may be required if it is desirable to transport the spent material a considerable distance over a rough terrain. A propellant would be required, and this might involve a problem of recovery and cycling unless gas or liquid is found in abundance in the lunar sub-surface.

B. Fluo-solids transfer: In the event part of the waste stream is in vapor or liquid form, a pipeline would be proposed for disposal of the spent rock. Possibly the vapor or liquid phase would serve as the propellant.

Transfer of Water of Recovery to Storage

1. Pipeline: A pipeline system would be required for transfer of liquid water to storage if it were desirable to maintain the liquid phase. The same problems would prevail as are involved in the use of water as a propellant, and, inasmuch as the pertinent data were outlined previously, the conditions will not be repeated.

2. Container: Containers made of metal or plastic could be employed for transfer of the liquid water, assuming it were desirable to maintain the liquid phase. Temperature control would be required and might be accomplished by employing insulation of the nature of polystyrene. Plastic containers would be favored because of weight, breakage, and expansion considerations.

Transfer of H₂ and O₂ to Storage

1. Pipeline: It is assumed hydrogen and oxygen would be produced and transferred to storage in the gaseous state. Pipelines of moderate pressure rating would serve this purpose.

2. Container: High-pressure metal drums might be utilized to transfer compressed hydrogen and oxygen.

Power Source

All of the transportation media discussed in this section would utilize electricity as the prime source of power for all operations.

B. Possible Lunar Applications of Shaped-Charges

Introduction: Shaped charges in their present form are a result of research which began with the discovery of the "Munroe effect" by Charles E. Munroe in 1888 at which time he reported that the detonation of a block of gun-cotton with indentations would reproduce those indentations as a mirror image when fired against an iron target with the indentations facing the target.

These initial shaped charges were unlined, but it was later discovered that lined shaped charges (see Figure 20) greatly increased the value of the shaped charge as a means of penetrating targets (either metal or rock). This discovery was credited to Dr. Wood in 1936. While investigating an accidental death caused by a blasting cap, he discovered that the dimpled shape of the end of the cap produced a high-velocity jet of metallic particles from the copper sheath composing the dimple (see Figure 21). The velocity of this jet for a #8 cap was determined to be 30,000 ft./sec. by Korolev and Pokrovski in 1944.

Following this discovery, several countries just prior to and during WW II developed military weapons utilizing the jet principle of lined cavity shaped charges. The most widely known of these weapons is the bazooka. Also many other military shaped-charge devices were developed for demolition purposes.

Present Industrial Uses: Shaped charges are presently being used in the oil industry for formation perforation in oil and gas wells, and in the steel industry for jet

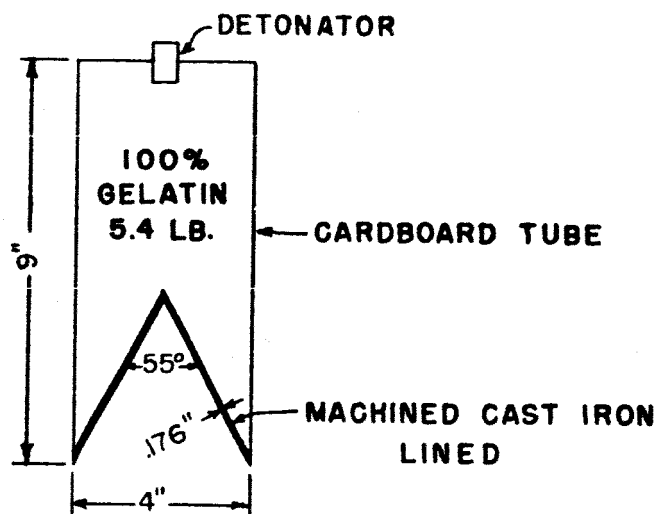


FIG. 20 DESIGN OF 4" DIAMETER LINED CAVITY SHAPE CHARGE

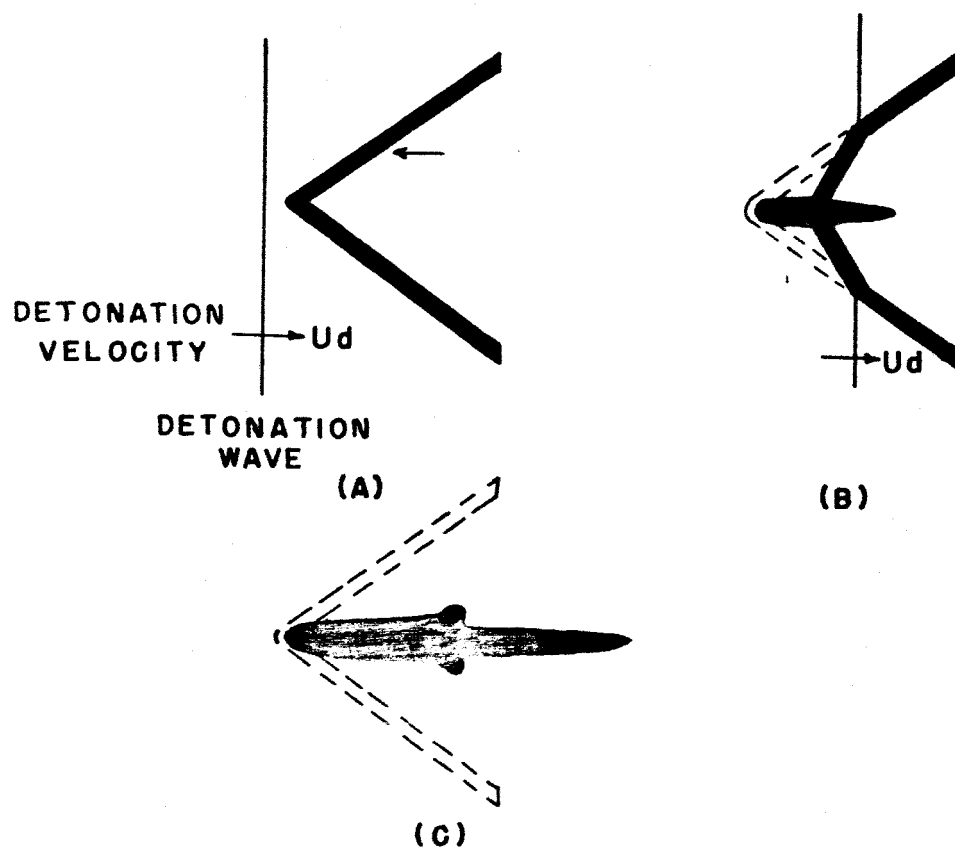


FIG. 21 SEQUENCE OF FORMATION OF METALLIC JET

tapping open-hearth furnaces. Also research has been conducted to determine the possibility of using shaped charges for secondary boulder blasting, the drilling of holes in rock for several purposes and the use of shaped charges for drifting. All of the uses have been feasible but at present are not economical.

Potential Lunar Uses: The primary potential uses for lined-cavity shaped charges on the moon are:

- 1) the drilling of holes in lunar rocks and soils for various purposes,
- 2) the breaking up of surface boulder for various reasons, and
- 3) the cleaning off of the lunar surface if necessary to expose the geological formation below.

Lined-cavity shaped charges have a great potential as a means of drilling shallow holes (approximately 15" - 25" deep) in lunar rocks. They could be used to drill holes in which anchor pin could be placed to anchor space craft to the surface of the moon, or for the anchoring of foundations for any type structure which it might be necessary to build.

A prime use could be to provide anchorage for mining equipment such as drills and loading machines. By anchoring drills to the moon surface it would be possible to develop the necessary axial thrust for the drilling operation without considering the weight of the machine itself. In the case of loading machines it would be possible to pick up larger loads if the machines were anchored. The use of lined cavity shaped charges to drill the anchor holes would be quick and efficient.

As for the placement of explosives in any type mining operation where required; shaped charges could be used to drill the blast holes, thereby eliminating the need for drill equipment. Also because of their compactness and simplicity of operation, they would eliminate many of the problems associated with drilling equipment.

Another use that may be required for initial exploration of the lunar surface is the breaking up of surface boulder, etc., that may be present and constitute an obstacle to mobile exploration equipment. Research has been conducted that confirms the feasibility of such a use, but it is uneconomical at the present for earth uses.

A use that has been suggested for geological exploration on earth, is the use of shaped charges to clean away surface material and expose the rock surfaces below. In the event that the lunar surface is covered with a layer of dust, shaped charges could be used to clean the surface for building sites, for geological exploration, and for mining operations.

Conclusions: From the previous discussion, it is considered feasible to use shaped charges on the moon for drilling holes, cleaning the lunar surface, and for breaking boulder. All of these uses being dependent on the problems and conditions existant.

The main advantage to using shaped charges are their compactness and simplicity of operation as compared to drill machines considering the hostile environment in which they will be used. Also the cost of shaped charges would be small relative to the develop of a drill for use under lunar conditions.

The main disadvantage is that a shaped charge can only be used once, and they would have to be shipped from earth. The weight of a shaped charge necessary to drill a 2 ft. hole would be approximately 4 lbs.

REFERENCES

- Austin, C. F., Lined-Cavity Shaped Charges and Their Use in Rock and Earth Materials. Bulletin 69 State Bureau of Mines and Mineral Resources, Socorro, New Mexico, 1959.
- Huttl, J. B. "The Shaped Charge for Cheaper Mine Blasting," Engineering and Mining Journal, May 1946, p. 58.

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REFERENCES

- Allenby, R. J. Chm. Coord. Com. (1965) NASA 1965 Summer Conference on Lunar Exploration and Space. National Aeronautics and Space Administration, Washington. Report of Geology Working Group, 77-160.
- Alter, D. (1959) The Alphonsus Story. Proceed., Lunar & Planet. Expl. Coll., N. Amer. Aviation, Inc., Downey, Cal., 1, 3-10.
- Bensko, J. and Shotts, R. Q. (1965) Lunar Resources. In: Advances in Space Science and Technology, Academic Press, New York, v. 7, 147-214.
- Delonis, S. L. (1966) The Challenge of the '70's---Mining on the Moon. Mining Engineering, 18, no. 1, 63-69.
- Donn, W. L., Donn, B. D. and Valentine, W. G. (1965) On the Early History of the Earth. Bull., Geol. Soc. Amer., 76, no. 3, 287-306.
- Elsmore, B. (1957) Radio Observations of the Lunar Atmosphere. Philosophical Mag., 2, 8th Ser., no. 20, 1040-1056.
- Fields, S. A. (1966) Behavior of Simulated Lunar Material in an Ultra High Vacuum Environment. Paper presented at 43rd Ann. Meeting, Ala. Acad. of Science, B'ham, Ala., April 1.
- Glaser, P. E., Wechsler, A. E. and George, J. H. B. (1964) Feasibility of Liquid Hydrogen Production on the Lunar Surface. Paper read at 3rd An. Meet. Working Group for Extraterrestrial Resources, Cape Kennedy, Nov. 18-20, 19 pages + 8 figures.
- Glaser, P. E., Wechsler, A. E. and Germale, A. E. (1965) Thermal Properties of Postulated Lunar Surface Materials. Ann. N. Y. Acad. Sci., 123, 656-670.
- Green, J. (1960) Geophysics as Applied to Lunar Exploration (Final Report). AFCRL Document No. AFCRL-TR-60-409. Obtainable from U. S. Dept. Comm., Office of Tech. Serv., Washington 25, D. C., 268 pages.
- Green, J. and Van Lopik, J. R. (1961) The Role of Geology in Lunar Exploration. In: Adv. in Space Sci. and Tech. Academic Press, New York, v. 3, 1-112.
- Green, J. (1965) A Study of the Feasibility of Using Nuclear Versus Solar Power in Water Extraction from Rocks. Final Report, Contract No. AF 19(628)-3292, Space and Information Systems Div., N. Amer. Aviation, Inc., Downey, Calif., Sept. 30. 353 pages, 64 tables, 141 figures.
- Halajian, J. D. (1962) Laboratory Investigation of 'Moon Soils'. Rept. No. ADK 04-04-621, Engr. Dept., Adv. Dev. Program, Grumman Aircraft Engr. Corp., 61 pages.

- Halajian, J. D. (1965) The Case for a Cohesive Lunar Surface Model. *Ann. New York, Acad. Sci.*, 123, 671-710.
- Jaffe, L. D. (1966) Lunar Dust Depth in Mare Cognitum. *J. Geophy. Res.* 71, no. 4, 1095-1103.
- Kuiper, G. P. (1959) The Moon. *J. Geophy. Res.*, 64, 1713-1720.
- Kuiper, G. P., Ed. (1960) *Photographic Lunar Atlas*. Univ. Chicago Press, Chicago.
- Lamar, D. L., and McGann, J. (1966) Shape and Internal Structure of the Moon. *Icarus*, 5, no. 1, 10-23.
- Levin, J. (1962) Thermal History of the Moon. In: *The Moon*, Z. Kopal & Z. K. Mikhailov, Eds. Academic Press, London, 157-167.
- Loomis, A. A. (1965) Interpretation of Lunar Alpha Scattering Data. *J. Geophy. Res.*, 70, 3841-3849.
- Lowman, P. D., Jr. (1963) The Relation of Tektites to Lunar Igneous Activity. In: *Space Sciences*, Vol. I, Goddard Space Flight Center Publications, 1215-1227.
- MacDonald, G. J. F. (1961) Interior of the Moon. *Science*, 133, 1045-1050.
- McCracken, C. W. and Dubin, M. (1964) Dust Bombardment on the Lunar Surface. In: *The Lunar Surface Layer*, J. W. Salisbury and P. E. Glaser, Eds., Academic Press, 179-214.
- Ness, N. F. (1966) Earth's Magnetic Field: A New Look. *Science*, 151, No. 3714, 1041-1052.
- O'Keefe, J. A. and Cameron, W. S. (1963) Evidence From the Moon's Surface Features For the Production of Lunar Granites. *Space Sciences, Publications of the Goddard Space Flight Center*, Vol. 1, 1284-1298.
- Opik, E. J. and Singer, S. F. (1960) Escape of Gases from the Moon. *J. Geophy. Res.*, 65, 3065-3070.
- Orowan, E. (1964) Continental Drift and the Origin of Mountains. *Science*, 146, no. 3647, 1003-1010.
- Paul, D. 3rd. (1965) Economic Analysis of Extraterrestrial Propellant Manufacture in Support of Lunar Exploration. Pre-print for 3rd Annual Meeting Working Group for Extraterrestrial Resources, Air Force Academy, Colo. Springs, Colo., Nov. 30-Dec. 2, 1965. 17 pages, 16 figures.
- Rosenberg, S. D., Guter, G. A. and Rothenberg, G. A. (1964) Requirements for on-site Manufacture of Propellant Oxygen from Lunar Raw Materials. Contrib. 263, paper presented at 3rd. Ann. Meeting of the Working Group on Extraterrestrial Resources, Cape Kennedy, Nov. 18-20. 5 pages, 11 tables, 6 figures.

- Ryan, J. A. (1965) Experimental Investigation of Ultra-High Vacuum Adhesion as Related to the Lunar Surface. Fourth Qtr. Prog. Rept. and First Year Summary. Missile & Space Systems Div., Douglas Aircraft Co., Inc., Santa Monica, Cal., Report SM-47914, 60 ill., 81 pages.
- Salisbury, John W. (1961) The Origin of Lunar Domes. Astrophys. J., 134, 126-129.
- Salisbury, J. W. (1962) Natural Resources of the Moon. Nature, 195, 423-427.
- Salisbury, J. W., Glaser, P. E. and Wechsler, A. E. (1963) The Implications of Water as a Lunar Resource. Lunar and Planetary Colloquium, North American Aviation, Inc., Downey, California, III, No. 3 (Nov.), 39-53.
- Salisbury, J. W. & Smalley, V. G. (1964) The Lunar Surface Layer. In: The Lunar Surface Layer, J. W. Salisbury and P. E. Glaser, Eds., Academic Press, New York, 411-443.
- Salisbury, J. W., Eckhard, D. H. and Hunt, M. S. (1965) The Lunar Environment. In: Handbook of Geophysics and Space Environments, United States Air Force, S. L. Valley, Sci. Ed., Chap. 19, 19-1 to 19-16.
- Shotts, R. Q., Grubbs, D. M., and Ahrenholz, H. W. (1963) Three Lunar Geochemical Models for a Study of Possible Systems for the Generation and Synthesis of Fuel on Extra-Terrestrial Launch Sites. Summary Report of MSFC, NASA, Bur. Engr. Res., U. of Ala., University, Ala., Contract NA58-5043, 73 pages.
- Shotts, R. Q. (1966) The Lunar Crust. 43rd Annual Meeting, Ala. Acad. of Science, Birmingham Sou. College, Apr. 1.
- Sinton, W. M. (1962) Temperatures on the Lunar Surface. In: Physics and Astronomy of the Moon, Z. Kopal, Ed. Academic Press, New York, Chap. 11, 407-428.
- Spock, L. E. (1953) Guide to the Study of Rocks. Harper and Brothers, New York, 256 pages.
- Urey, H. C., Elsasser, W. M. and Rochester, M. G. (1959) Note on the Internal Structure of the Moon. Astrophys. J., 129, 842-848.
- Urey, H. C. (1961) On Possible Parent Substances for the C₂ Molecules Observed in the Alphonsus Crater. Astrophys. J., 134, 268-269.
- Watson, K., Murray, B. C. and Brown, H. (1961) On the Possible Presence of Ice on the Moon. J. Geophys. Res., 66, 1598-1600.

- Wehner, G. K. (1964) Sputtering Effects on the Lunar Surface. In: The Lunar Surface Layer, Academic Press, New York, 313-322.
- Weil, N. A. (1965) Lunar and Planetary Surface Conditions. Advances in Space Science and Technology. Supplement 2, Academic Press, New York, 218 pages.
- Westhusing, J. K. and Crowe, C. (1965) Techniques for Lunar Water Exploration. Final Report, Contract No. AF 19 (628)-3287, Sept. 30, Air Force Cambridge Research Laboratories, 398 pages, Appendix, 49 tables and 131 figures.

I. INTRODUCTION

Several investigations have shown that mechanical stress can induce reversible changes in the electrical characteristics of p-n junctions.¹⁻⁵ In these investigations, large anisotropic stresses have been introduced into the junctions of diodes and transistors resulting in large changes in saturation currents of diodes and in current-gain for transistors. These changes have been attributed to stress induced changes in the energy band structure of the material and in particular to changes in the band gap.⁶ Recent experimental investigations have shown that the reverse breakdown voltage in Si and Ge diodes is also stress sensitive.^{7,8} The breakdown voltage in Si is found to be linearly related to uniaxial compression stress, while in Ge, the breakdown voltage is found to be a more complex function of the stress. The stress coefficient in Si is approximately equal to the coefficient found for band gap lowering under hydrostatic pressure. In Ge, the breakdown voltage is found to increase and then to decrease as stress increases.

The purpose here is to discuss the effects of multiple energy bands on the stress dependence of breakdown and to evaluate the order of magnitude of these stress induced changes in the breakdown voltage of Ge and Si diodes. A theoretical discussion is given which is based on Shockley's "Simple Model for Secondary Ionization"⁹ and the stress induced changes in the energy band structure of semiconductors.

II. THEORY

A. Simple Ionization Model

The ionization model to be discussed here for the unstressed junction was introduced by Shockley.⁹ The model is empirical in that it involves four-parameters, three of which are adjustable. It includes neither the energy band structure for energies greater than 1 ev from the band edges nor the effective masses of hot carriers. However, the model is found to be in reasonable agreement with experiment.

In the unstressed crystal, the four parameters of the model are as follows:

E_R = Energy of the "Raman" vibration mode.

L_R = Mean-free-path between scattering by "Raman" modes.

E_i = Threshold energy measured from the band edge above which a carrier may produce a hole-electron pair.

L_i = Mean-free-path between ionizations for a carrier with energy greater than E_i .

Using these parameters, an electron with energy greater than E_i generates on the average L_i/L_R phonons per ionization. In the low field limit, which has been shown to be valid for Ge and Si, the average number of scattering events, C , per ionization is

$$C = \frac{L_i}{L_R} \exp(E_i/qL_R F) , \quad (1)$$

where F is the electric field. The average energy, E_i^* , gained from the field by the carrier per ionization is then

$$E_i^* = \frac{L_i E_R}{L_R} \exp(E_i / q L_R F), \quad (2)$$

or

$$E_i^* = a \exp(b/F), \quad (3)$$

where a and b are constants of the material.

The secondary multiplication coefficient, $\alpha(F)$, is

$$\alpha(F) = \frac{qF}{E_i^*} = \frac{qFL_R}{L_i E_R} \exp(-E_i / q L_R F). \quad (4)$$

To extend the model to a stressed semiconductor, the effects of multiple conduction and valence levels on the ionization process must be considered.

B. Strain Dependent Ionization Theory

Mechanical strain has the effect of altering the energy band structure of semiconductors. The effects of strain on the conduction and valence band edge points for Ge and Si are reviewed in Appendix A. Under a general strain, the valence band edge not only shifts in energy, but also splits into two levels. The conduction band edge points also shift in energy both relative to the valence levels and to each other. The net results are different energy gaps depending on which valence and conduction band edge points are used to calculate the gap.

In the unstressed crystal, it is not necessary to know the exact dependance of the ionization energy on the energy band structure since this can be determined experimentally. Shockley assumes that for Si, E_i is equal to the band gap.⁹ Most investigators,^{10,11} however, find a better fit of theory to experimental data using an E_i slightly

larger than the band gap. This is particularly true in Ge. To obtain the numerical results for the effect of stress on breakdown voltage, a model which relates the ionization energy to the energies of the various bands is required. Such a model is discussed in a later section. For the present general development more general assumptions about the ionization process are sufficient.

Consider electron ionization first. In this ionization process, a hot electron in one of the conduction minima ($\langle 111 \rangle$ direction minima in Ge and $\langle 100 \rangle$ direction minima in Si) excites an electron from one of the valence bands to one of the conduction levels. The result being the creation of an electron-hole pair. The ionization threshold energy is the minimum energy at which the above process can occur. This energy is expected to depend upon the shape of the energy bands in which the ionizing electron and the created pair are located as well as the band edge point energies of the various bands. In the unstressed crystal, all the conduction minima are located at the same energy so there can be only two different threshold energies--one associated with the heavy hole band and one associated with the light hole band. With a stress condition, the conduction levels are split in energy and consequently the threshold energies for the various nondegenerate conduction levels should be different.

Here it is assumed that the ionization threshold energy depends upon the conduction level in which the ionizing hot electron is located and the valence level in which the created hole is located. This assumes that the created electron is located either in the same

energy minimum as the hot electron or is located in the equivalent energy minimum in the opposite direction in k-space. This is a reasonable assumption, since crystal momentum can be more easily conserved in this process.¹²

An ionization threshold energy E_{nm} can then be associated with each of the combinations of valence and conduction levels, where n denotes the conduction level and m denotes the valence level. There are six such combinations for Si and eight for Ge. Each of the ionization processes may also have a different mean free path denoted by L_{nm} .

It will be assumed here that L_R and E_R are not functions of stress, and that L_R is the same for all the conduction band minima.

Using the above definitions, the number of ionizations which leaves a hole in the valence level m and an electron in conduction level n per scattering event, is denoted by $1/C_{nm}$. From Eq. (1) this is

$$\frac{1}{C_{nm}} = \frac{L_R}{L_{nm}} \exp(-E_{nm}/qL_R F) . \quad (5)$$

The total number of ionizations per scattering event is obtained by summing over the ionization processes for a hot electron in a given conduction minimum and then averaging over the conduction levels. In averaging over the conduction levels, $1/C_{nm}$ must be multiplied by the fraction of hot electrons $n_{hn}/\sum_n n_{hn}$, in each conduction minimum. The average number of ionizations per scattering event is then

$$\frac{1}{C} = \frac{\sum_{n=1}^{\beta} n_{hn} \sum_{m=1}^{\gamma} \frac{L_R}{L_{nm}} \exp(-E_{nm}/qL_R F)}{\sum_{n=1}^{\beta} n_{hn}}, \quad (6)$$

where γ is the number of valence levels and β is the number of conduction levels.

The evaluation of the above formal expression requires an assumption on the distribution of hot electrons among the conduction levels. This distribution of hot electrons depends upon the importance of intervalley and intravalley scattering. If intervalley scattering is negligible, the conduction minima can be considered as independent of each other and

$$n_{hn} \propto \exp(-E_{cn}/kT), \quad (7)$$

where E_{cn} is the band edge energy of the conduction level. This is just the equilibrium distribution of electrons among the valleys. On the other hand, if intervalley scattering is predominate, the electrons are more uniformly distributed among the levels because of the increased effective temperature of the hot electrons. On the basis of Shockley's model for ionization, the hot electrons in a given conduction minima are distributed in energy according to the relationship

$$n(E) \propto \exp(-E/qL_R F). \quad (8)$$

When intervalley scattering dominates, one would also expect this distribution to hold for electrons among the conduction levels and in this case

$$n_{hn} \propto \exp(-E_{cn}/qL_R F) . \quad (9)$$

To keep the assumption more general, the hot electrons are assumed to be distributed among the valleys according to the relationship

$$n_{hn} \propto \exp(-E_{cn}/E_1) , \quad (10)$$

where E_1 equals kT and $qL_R F$ for the cases considered above. As is subsequently shown, the low stress case and the very high stress case are independent of the choice of E_1 .

The total number of ionizations per scattering event then becomes

$$\frac{1}{C} = \frac{\sum_{n=1}^{\beta} \exp(-E_{cn}/E_1) \sum_{m=1}^{\gamma} \frac{L_R}{L_{nm}} \exp(-E_{nm}/qL_R F)}{\sum_{n=1}^{\beta} \exp(-E_{cn}/E_1)} . \quad (11)$$

The secondary multiplication coefficient for electrons is then given by

$$\alpha(F) = \frac{qFL_R}{E_R} \frac{\sum_n \exp(-E_{cn}/E_1) \sum_m \frac{1}{L_{nm}} \exp(-E_{nm}/qL_R F)}{\sum_n \exp(-E_{cn}/E_1)} . \quad (12)$$

The value of L_{nm} in Eq. (12) may be different for holes created in the lower valence level as compared to holes created in the upper valence level. One would also expect L_{nm} to be slightly dependent upon the direction of the applied field. For example, if the applied field is along a conduction valley direction, one expects a smaller value of L_{nm} for an electron created in the energy minimum along the field direction than for the other energy minimum. The difference between these values depends upon intervalley and intravalley scattering

of hot electrons. If there is sufficient scattering to produce essentially a random distribution of the hot electrons both in and among the conduction valleys, L_{nm} should be essentially the same for all valleys. Sufficient information is not available to permit a detailed evaluation of this parameter. It is also noted that L_{nm} is a linear factor influencing $\alpha(F)$, while the ionization energy E_{nm} is exponentially related to $\alpha(F)$. Thus small changes in E_{nm} tend to be more important in determining $\alpha(F)$ than small changes in L_{nm} . It will therefore be assumed that L_{nm} is the same for all ionization processes. This assumption makes the stress dependence of the secondary multiplication coefficient independent of the direction of the electric field.

For Ge with an electric field in the [100] direction, the component of electric field along each of the valley directions is the same, and the assumption of a constant L_{nm} for all the valleys should be valid. The assumption should be least valid for a field in the [111] direction. For Si, the assumption should be most accurate for a field in the [111] direction and least accurate for a field in the [100] direction.

Assuming that L_{nm} is constant, it can readily be seen from Eq. (12) by considering the unstressed case ($E_{nm} = E_i$) that

$$L_{nm} = \gamma L_i. \quad (13)$$

Equation (12) becomes

$$\alpha(F) = \frac{qFL_R}{E_R L_i \gamma} \frac{\sum_n \sum_m \exp(-E_{cn}/E_1 - E_{nm}/qL_R F)}{\sum_n \exp(-E_{cn}/E_1)}. \quad (14)$$

This is the basic equation used to describe stress dependent voltage breakdown, when electron ionization is the dominant process.

Although the concepts for hole ionization are similar to electron ionization, there are important differences in the details. If the difference in effective mass for the two hole bands is neglected and the ionization energy is assumed to depend only upon the band on which the hot hole exists and upon the conduction minimum to which the electron is excited, the evaluation of hole ionization is very similar to that for electron ionization. The difference is that the average number of ionizations per scattering event is obtained by summing over the conduction levels and averaging over the valence levels. This leads to the expression

$$\alpha(F) = \frac{qFL_R}{E_R L_i \beta} \frac{\sum_m \sum_n \exp(E_{vm}/E_1 - E_{nm}/qL_R F)}{\sum_m \exp(E_{vm}/E_1)}, \quad (15)$$

where E_{vm} is the energy of the valence levels.

The large difference in density of states or effective mass for the two valence bands, especially in Ge, makes the neglect of these differences in the above expression open to question. There are, however, factors which make the above expression a better approximation than it would at first appear. First, the average energy of the holes is on the order of E_R which is larger than the thermal energy and, for large energies, the density of states for the two bands become more equal. In Si the density of states are not too different for energies larger than about 0.02 ev.¹³ For Ge the energy is considerably larger. A second factor for unequal hole masses is that L_R is different for the

two bands. For a single spherical energy band, L_R has been shown to depend upon the mass as $m^{-2.14}$. This partially compensates for the difference in the density of states of the two bands. The compensating effects in the two bands can be thought of in the following manner. The holes in the "light" hole band are more rapidly accelerated than the "heavy" holes to energies sufficient to produce optical phonons or to produce ionizations. Thus, while there are fewer holes in the light hole band, they undergo scatterings and produce ionizations at a faster rate which tends to produce some compensation. Here the purpose is to discuss the major features of stress effects on breakdown so that the simple expression of Eq. (15) is sufficient.

C. Strain Dependent Breakdown

Even when the ionization coefficient is known, the calculation of the breakdown voltage of a p-n junction is difficult, especially when the ionization coefficients for holes and electrons are unequal.¹⁰ Including the effect of stress further complicates the calculation. A simplifying approximation is made to obtain a tractable model. Because of the exponential dependence of α upon $1/F$, the major contributions to α come from the depletion region near the maximum field point. Let α_m be the value of α at the maximum field point, and consider the effect of stress upon α_m . If the maximum junction field is unchanged when stress is applied (i.e. if the junction voltage is unchanged), the ionization coefficient changes and hence the current multiplication factor for the junction changes. On the other hand, if α_m is to remain

constant under stress, the maximum field must change. The approximation which is made here is that at a constant current multiplication factor for the junction, the maximum junction field is changed such that α_m remains constant. The following development is for electron ionization; the corresponding development for hole ionization is similar.

To obtain the change in maximum field required to keep α_m constant, let

$$E_{nm}(\sigma) = E_i + \Delta E_{nm} , \quad (16)$$

and

$$F = F_o + \Delta F , \quad (17)$$

where E_i and F_o are the unstressed values and $E_{nm}(\sigma)$ is the stress dependent ionization energy. Then for electron ionization neglecting second order effects,

$$\begin{aligned} \alpha_m(F_o + \Delta F) &= \frac{qF_o}{E_R} \left(1 + \frac{\Delta F}{F_o}\right) \frac{L_R}{\gamma L_i} \exp[-E_i(1 - \Delta F/F_o)/qL_R F_o] \\ &\times \frac{\sum_n \sum_m \exp(-\Delta E_{cn}/E_1 - \Delta E_{nm}/qL_R F_o)}{\sum_n \exp(-\Delta E_{cn}/E_1)} . \end{aligned} \quad (18)$$

By equating this to the unstressed value of $\alpha_m(F_o)$, it is found that

$$1 = \left(1 + \frac{\Delta F}{F_o}\right) \frac{1}{\gamma} \exp(E_i \Delta F / qL_R F_o^2) \frac{\sum_n \sum_m \exp(-\Delta E_{cn}/E_1 - \Delta E_{nm}/qL_R F_o)}{\sum_n \exp(-\Delta E_{cn}/E_1)} . \quad (19)$$

This expression relates the change in the maximum junction electric field to the stress induced changes in the energy levels.

To obtain the change in junction voltage at a constant current multiplication factor, the change in maximum junction field must be

related to the junction voltage. The maximum field is proportional to $V^{1/2}$ for a step junction.¹⁵ Thus for small changes

$$\frac{\Delta V}{V_B} \approx 2 \frac{\Delta F}{F_o}, \quad (20)$$

where V_B is the unstressed breakdown voltage at a constant current level. For most p-n junctions, the step junction approximation is reasonably accurate at large reverse bias.

For small changes in the breakdown voltage ($\Delta V/V_B \ll 1$), Eq. (19) can be solved for the change in breakdown voltage to give

$$\frac{\Delta V}{V_B} = - \frac{2}{(1 + E_i/qL_R F_o)} \ln \left\{ \frac{1}{\gamma} \frac{\sum_n \sum_m \exp(-\Delta E_{cn}/E_1 - \Delta E_{nm}/qL_R F_o)}{\sum_n \exp(-\Delta E_{cn}/E_1)} \right\}. \quad (21)$$

For hole ionization a similar development leads to

$$\frac{\Delta V}{V_B} = - \frac{2}{(1 + E_i/qL_R F_o)} \ln \left\{ \frac{1}{\beta} \frac{\sum_n \sum_m \exp(\Delta E_{vm}/E_1 - \Delta E_{nm}/qL_R F_o)}{\sum_m \exp(\Delta E_{vm}/E_1)} \right\}. \quad (22)$$

In the low stress region ($\Delta E_{nm}/qL_R F_o \ll 1$ and $E_{cn}/E_1 \ll 1$), the equations for both electron and hole ionization simplify to

$$\frac{\Delta V}{V_B} = \frac{2}{qL_R F_o (1 + E_i/qL_R F_o)} \frac{1}{\gamma \beta} \sum_{n,m} \Delta E_{nm}. \quad (23)$$

In this limit, the factor $(1/\gamma\beta) \sum \Delta E_{nm}$ is the simple average of the changes in the ionization threshold energies.

To carry the development further and obtain numerical results requires a model for the changes in the ionization threshold energies with stress. One assumption is that the ionization threshold energy

is equal to the band gap. This implies that momentum is supplied by phonons. Neglecting phonon assisted processes the ionizing electron must have both enough energy to create the hole-electron pair (E_g) and also enough excess energy to conserve both momentum and energy between the single incident particle and the three final particles. For a direct band gap material the minimum energy is readily found to be $3E_g/2$. For an indirect band gap material such as Ge and Si, it has recently been shown¹² that a consideration of energy and crystal momentum conservation leads to an expression of the form

$$E_i \simeq k_1 + k_2 E_g, \quad (24)$$

where k_1 and k_2 are constants depending in rather complex ways on the effective masses of the three particles. The effective masses entering into k_1 and k_2 are not the band edge effective masses, but are the masses which give the best fit to the energy bands over the energy range from zero to the ionization energy. Based upon this model, the ionization threshold energy between a conduction level and a valence level is

$$E_{nm} = k_1 + k_2 (E_{cn} - E_{vm}). \quad (25)$$

This is the model used in this work to relate the band structure to the ionization energy.

Stress can have two effects on E_{nm} as defined above through changes in the energy levels ($E_{cn} - E_{vm}$) and through changes in the shape (or effective mass) of the energy levels which results in changes in k_1 and k_2 . The effect of stress on the band edge energy levels is

known but the effect of stress on the effective mass of the bands especially at large energies has not been as thoroughly investigated. Some work has been done on the effective masses near the band edges, but the effective mass at large energies probably changes less than near the band edges, especially for the hole bands. Near the band edges there is no first order change in the effective mass with stress for electrons.^{16,17} Also under compression stress in the [100] and [111] directions there is no first order change in the effective mass of the lower valence level.¹⁸ Based upon the above facts, k_1 and k_2 have been taken as independent of stress for our first order model and the changes in ionization energy are taken to be

$$\Delta E_{nm} = k_2(\Delta E_{cn} - \Delta E_{vm}). \quad (26)$$

For equal hole and electron masses, k_2 is 0.59 for electron ionization in Ge and 0.63 for hole ionization in Ge and for both electron and hole ionization in Si.¹²

Using the above model for ionization, the change in breakdown voltage at low stress is given from Eq. 24 as

$$\frac{\Delta V}{V_B} = \frac{2k_2 KP}{E_i} \left(1 + \frac{qL_R^F}{E_i}\right)^{-1}, \quad (27)$$

where K is the coefficient relating the change in band gap to hydrostatic pressure and P is the hydrostatic component of stress.

Typical values of the parameters in Eq. (27) are listed in Table I. Using these values, Eq. (27) reduces to

TABLE I: Typical Values of K , F_o , L_R and E_i in Ge and Si

	$K(10^{-12} \text{ ev cm}^2/\text{dyne})$	$F_o(10^5 \text{ volts/cm})$	$L_R(A^\circ)$	$E_i(\text{ev})$
Si	-1.5^a	5^b	$50-70^d$	$1.3^{f,g}$
Ge	5.0^e	0.82^c	65	$1.0^f, 0.93^g$

a. W. Paul and G. L. Pearson, Phys. Rev., 98, 1755 (1955).

b. Ref. 9

c. R. Yee, J. Murphy, A. D. Kurtz, and H. Bernstein, J. Appl. Phys. 30, 596 (1959).

d. Ref. 10

e. P. W. Bridgman, Proc. Am. Acad. Arts Sci. 79, 129 (1951).

f. Values calculated for electron ionization, Ref. 12.

g. Values calculated for hole ionization, Ref. 12.

$$\text{Si: } \frac{\Delta V}{V_B} = -1.2 \times 10^{-12} P \text{ cm}^2/\text{dyne}, \quad (28)$$

$$\text{Ge: } \frac{\Delta V}{V_B} = 6.0 \times 10^{-12} P \text{ cm}^2/\text{dyne}. \quad (29)$$

As can be seen from Eq. (27), at low stress levels, $\Delta V/V_B$ is independent of stress orientation since only the hydrostatic component of stress remains in the expressions. It is significant that at low stress levels, $\Delta V/V_B$ has an opposite sign for Ge and Si.

Returning to Eq. (22), it is seen that in the high stress case, the minimum conduction level and the maximum valence level will predominate, i.e., the ΔE_{nm} with the largest negative value. The corresponding ΔE_{cn} is negative. In general for uniaxial compression stresses at least one of the ΔE_{nm} 's will be negative for both Ge and Si. Therefore, for high stresses, $\Delta V/V_B$ decreases for both materials, and is independent of the value of E_1 . This is true for both electron and hole ionization.

For a given value of the ratio $E_1/qL_R F_o$, the change in breakdown voltage under stress can be calculated from Eqs. (21) and (22) for electron and hole ionization respectively. To account for the increased effective temperature of the carriers in the high field, the value $E_1 = qL_R F_o$ has been used in most of the calculations. The following deformation potentials were used in evaluating the shifts in the energy levels (see Appendix A):

Ge	Si
$D_u = 3.15$	$D_u = 2.04$
$D'_u = 6.06$	$D'_u = 2.68$
$\Xi_u = 19.2$	$\Xi_u = 11$
$D_d - (\Xi_d + \Xi_u/3) = 4.82$	$D_d - (\Xi_d + \Xi_u/3) = -1.44$

The calculated changes in breakdown voltage in Ge with stress for electron and hole ionization are shown in Figs. 1 and 2 for uniaxial stresses in the [100], [111], and [110] directions. The curves are plotted in terms of a normalized stress and a normalized voltage change given by the expressions

$$\sigma' = (E_g / qL_R F_o) \sigma, \quad (30)$$

$$\frac{\Delta V'}{V_B} = \frac{1}{2} \left(1 + \frac{E_i}{qL_R F_o} \right) \frac{\Delta V}{V_B}.$$

The curves illustrate the increase in breakdown voltage in Ge at low stresses, independent of the stress orientation, and the decrease in breakdown voltage at large stress values. It is also noted that for electron ionization, the changes for the [100] direction require approximately an order of magnitude larger stress than the other two directions.

A comparison of the theoretical changes (for electron ionization) in breakdown voltage for two values of E_1 are shown in Fig. 3. The two values of E_1 ^{are} ~~and~~ kT and $qL_R F_o$. It is recalled that the value kT

the saturation current. The reason this is necessary is that the saturation current is also stress sensitive. The multiplication factor, M is related approximately to the applied voltage, V_A , by¹⁹

$$M = \frac{1}{1 - (V_A/V_B)^n}, \quad (31)$$

where n is a constant for the device. The diode current, I , is given by

$$I = I_s M, \quad (32)$$

where I_s is the reverse saturation current. Combining Eqs. (30) and (31) gives

$$V_A = V_B (1 - I_s/I)^{1/n}. \quad (33)$$

If $M \gg 1$,

$$V_A = V_B (1 - \frac{1}{n} \frac{I_s}{I}). \quad (34)$$

Neglecting second order terms, the relative change in the applied voltage at constant current is

$$\frac{\Delta V_A}{V_B} \approx \frac{\Delta V}{V_B} - \frac{\Delta I_s}{nI}. \quad (35)$$

The change in applied junction voltage is then less than the change in the breakdown voltage by the factor $V_B \Delta I_s / nI$. This is negligible only if nI is large compared with ΔI_s . Using Eq. (35), $\Delta V/V_B$ can be evaluated from an experimental plot of current versus voltage as a function of stress if ΔI_s is known as a function of stress. For a uniformly stressed junction in which the total junction area is stressed, $\Delta I_s/I_{s0}$ is given by⁶

$$\frac{\Delta I_s}{I_{so}} = \frac{1}{\gamma\beta} \sum \exp\left(\frac{\Delta E_{cn} - \Delta E_{vm}}{kT}\right) - 1 = (f(\sigma) - 1), \quad (36)$$

where I_{so} is the unstressed saturation current. This gives the following expression for $\Delta V_A/V_B$

$$\frac{\Delta V_A}{V_B} \approx \frac{\Delta V}{V_B} - \frac{(f(\sigma) - 1)}{nM_o}, \quad (37)$$

where M_o is the multiplication factor between the unstressed saturation current and the current at which V_A is measured.

In Si, it has been found experimentally that uniaxial compression stress causes a linear decrease in $\Delta V_A/V_B$ by the factor^{7,8}

$$\frac{\Delta V_A}{V_B} \approx (-1 \times 10^{-12} \text{ cm}^2/\text{dyne}) \sigma, \quad (38)$$

where σ is the magnitude of the uniaxial stress. The theoretical proportionality constant is $-0.4 \times 10^{-12} \text{ cm}^2/\text{dyne}$ from Eq. (28) where $\sigma = P/3$. The theoretical value was calculated using the value $-1.5 \times 10^{-12} \text{ ev cm}^2/\text{dyne}$ for the hydrostatic pressure dependance of the band gap. Although this value is normally used, there is some variation in it depending on the method of measurement and the stress level.²⁰ In fact, it has been shown that the coefficient is stress dependant and at high stress levels, it is approximately $-2.5 \times 10^{-12} \text{ ev cm}^2/\text{dyne}$.²¹ Using the latter value gives a proportionality constant in Eq. (28) of approximately $-0.67 \times 10^{-12} \text{ cm}^2/\text{dyne}$.

As predicted by the theory, very little if any variation in the phenomenon with crystal orientation is seen experimentally in Si.^{7,8}

Preliminary measurements on breakdown voltage changes with hydrostatic pressure have given results which were an order of magnitude smaller than those for uniaxial stress.⁸ The present theory predicts that the voltage changes induced by hydrostatic pressure should be three times those of uniaxial stresses. At the present time, there is no explanation for these results.

Rindner has made measurements of the breakdown voltage change as a function of uniaxial stress in Ge diodes.⁷ The experimental points in Fig. 4 are the results he obtained from a [110] and a [100] uniaxial stress. The solid curves in the figure were calculated using the theory for hole ionization. The hole ionization curves were used because the secondary multiplication factor for holes is larger in Ge. The normalizing factor $E_g/qL_R F_0$ was considered as an adjustable parameter in fitting the theory to experiment. The values needed to fit the experimental data are approximately 8.5 and 16 for the [110] and [100] directions respectively. These values are in good agreement with the value of 12.6 calculated from the data in Table I. Attempts to fit the theory to published experimental data taken for [111] oriented uniaxial stress⁷ have been less successful. It should be noted that the data can also be made to agree with the theory for electron ionization by a suitable choice of $L_R F_0$. For the [100] direction, however, an unreasonably small value of $L_R F_0$ is required to produce a good fit to the data. It is difficult to draw too many conclusions from these comparisons without knowing the repeatability of the experimental results and the conditions under which the data was obtained. As

shown in Fig. 4, the experimental results and theoretical curves deviate from each other for low stress levels. This could result from nonuniform breakdown in the junction due to microplasma and surface effects.

V. DISCUSSION

The theoretical model for stress induced changes in breakdown voltage is in generally good agreement with experiment. In view of the simple model used for breakdown and the assumptions necessary to arrive at an analytical expression for the effect, it is surprising that the theory agrees as well as it does. The fact that the theory predicts an orientation dependence in Ge but no such dependence in Si in agreement with the experimental observations, lends considerable support to the theory.

Care must be exercised when comparing the theory to experiment since most practical devices do not exhibit uniform breakdown. Also, it is difficult to determine what percentage of the multiplication factor results from hole ionization as compared to electron ionization. These factors are necessary to make accurate comparison between theory and experiment. The comparison for Ge made in the preceding section was based on the assumption that the ionization energy is that of holes.

APPENDIX A

Both Ge and Si have multiple conduction minima in k-space. Ge has eight such minima which lie in the $\langle 111 \rangle$ direction and are located at the L_1 point in k-space while silicon has six conduction minima which occur in the $\langle 100 \rangle$ direction and are located approximately 85% of the distance from $k = (000)$ to the X_1 symmetry point. The maximum valence levels, Γ'_{25} , for both Ge and Si are located at $k = (000)$. The Γ'_{25} level is degenerate in energy. If the crystal is mechanically deformed, the crystal symmetry and the lattice spacings are altered and hence the energy bands change.

Herring and Vogt have considered the effect of mechanical strain on the conduction minima in both Ge and Si.²² The results of their work are summarized in Table II. The valley directions are identified by the subscripts on the conduction energy level changes ΔE_c 's. The E 's are deformation potential constants and the e 's are conventional strains. Table III lists some of the values of the deformation potential constants. The values appearing in brackets are theoretical values calculated by Kleinman, et al.²³⁻²⁵

The effects of mechanical strain on the valence levels of Ge and Si are much more complicated than the effects on the conduction levels. Kleiner and Roth have considered the effects of strain on the Hamiltonian of the valence band edge.²⁶ Diagonalizing their expression for the Hamiltonian gives the following expression for the change in energy of the valence level²⁷

$$\Delta E = D_d e \pm \left[\left(\frac{2}{3} D_u \right)^2 (e_1^2 + e_2^2 + e_3^2 - e_1 e_2 - e_1 e_3 - e_2 e_3) + \frac{1}{3} (D'_u)^2 (e_4^2 + e_5^2 + e_6^2) \right]^{1/2}. \quad (A1)$$

The D's appearing in the above expression are the valence band deformation potential constants. From Eq. (A1), it is seen that there is not only a shift of the level due to D_d , but also a splitting of the level due to D_u and D'_u , which removes the degeneracy. For convenience of notation, let the upper band, positive sign of Eq. (A1), be ΔE_{V1} and the lower band, negative sign, be ΔE_{V2} .

TABLE II. Equations describing the change in the band edge points in the conduction band of Ge and Si as a function of strain.

Valley Direction	Band Edge	Energy
Ge		
$[111], [\bar{1}\bar{1}\bar{1}]$	ΔE_{c1}	$(\Xi_d + \Xi_u/3)e + \Xi_u(e_4 + e_5 + e_6)/6$
$[1\bar{1}\bar{1}], [\bar{1}11]$	ΔE_{c2}	$(\Xi_d + \Xi_u/3)e + \Xi_u(e_4 - e_5 - e_6)/6$
$[1\bar{1}1], [\bar{1}1\bar{1}]$	ΔE_{c3}	$(\Xi_d + \Xi_u/3)e + \Xi_u(-e_4 + e_5 - e_6)/6$
$[11\bar{1}], [\bar{1}\bar{1}1]$	ΔE_{c4}	$(\Xi_d + \Xi_u/3)e + \Xi_u(-e_4 - e_5 + e_6)/6$
Si		
$[100], [\bar{1}00]$	ΔE_{c1}	$\Xi_d e + \Xi_u e_1$
$[010], [0\bar{1}0]$	ΔE_{c2}	$\Xi_d e + \Xi_u e_2$
$[001], [00\bar{1}]$	ΔE_{c3}	$\Xi_d e + \Xi_u e_3$

TABLE III. Deformation Potential Coefficients (ev/unit dilation) for Ge and Si. (Kleinman's theoretical values are shown in brackets.)

Coefficient	Si	Ge
D_d	[-2.09]	[-2.09]
D_u	2.04^a , [3.74]	3.15^b , [3.74]
D'_u	2.68^a , [4.23]	6.06^b , [3.6]
Ξ_d	[-4.99]	[-10.16]
Ξ_u	11^c , 8.3^d , [+9.6]	19.2^e , [11.4]
Ξ'_u	5.7^f	
$D_d - (\Xi_d + \frac{1}{3} \Xi_u)$	-1.44^g , [-0.30]	4.82^g , [4.27]

a. J. C. Hensel and G. Feher, Phys. Rev. 129, 1041 (1963).

b. J. J. Hall, Phys. Rev. 128, 68 (1962).

c. D. K. Wilson and G. Feher, Phys. Rev. 124, 1968 (1961).

d. J. E. Aubrey, W. Gubler, T. Henningsen and S. H. Koenig, Phys. Rev. 130, 1667 (1963).

e. H. Fritzche, Phys. Rev.

f. J. C. Hensel and H. Hasegawa, paper presented at the International Conference on the Physics of Semiconductors, Paris, July 1964, and private communications.

g. W. Paul, J. Phys. Chem. Solids 8, 196 (1959).

APPENDIX B: Effect of Stress on V_o .

The applied voltage differs from the junction voltage in reversed biased junctions by the built-in potential, i.e.

$$V = V_A + V_o, \quad (B1)$$

where V is the junction voltage, V_A is the applied voltage, and V_o is the built-in voltage. Mechanical stress not only changes the junction voltage, but it also can change the built-in voltage. The relative change in the applied voltage at breakdown is

$$\frac{\Delta V_A}{V_B} = \frac{\Delta V}{V_B} - \frac{\Delta V_o}{V_B}. \quad (B2)$$

The built-in voltage for a step junction is

$$V_o = \frac{kT}{q} \ln \left(\frac{N_A N_D}{n_i^2} \right), \quad (B3)$$

when N_A and N_D are the acceptor and donar concentrations on the p and n side of the junction respectively and n_i is the intrinsic carrier concentration ($n_i^2 = pn$).

Wortman, Hauser, and Burger have treated the effect of stress on p and n.⁶ Using their results and forming the pn product gives

$$n_i^2 = pn = p_o n_o f(\sigma), \quad (B4)$$

when $p_o n_o$ is the unstressed intrinsic carrier concentration. The factor $f(\sigma)$ is given by

$$f(\sigma) = \frac{1}{\gamma\beta} \sum \exp\left(\frac{\Delta E_{cn} - \Delta E_{vm}}{kT}\right) . \quad (B5)$$

The change in V_o divided by V_B becomes

$$\frac{\Delta V_o}{V_B} = - \frac{kT}{qV_B} \ln f(\sigma) . \quad (B6)$$

At room temperature $qL_R F_o / E_g$ is approximately equal to kT for Ge so that

$$\frac{\Delta V_o}{V_B} \approx 4 \frac{E_i}{qV_B} \frac{\Delta V}{V_B} . \quad (B7)$$

Therefore, for Ge, if V_B is larger than several volts, $\Delta V_o / V_B$ can be neglected compared to $\Delta V / V_B$.

In Si, $qL_R F_o$ is approximately 10 kT so that, except for hydrostatic stresses, the exponential terms will contribute to the built-in potential at a lower stress level than they do for the junction voltage. Therefore, if V_B is not large, the change in the built-in potential can reduce the change in the applied voltage. In fact, if V_B is on the order of one volt, the built-in potential change can dominate the applied voltage change.

Footnotes and References

- * This work was supported in part by the National Aeronautics and Space Administration under Contract No. NASr-222.
- ¹ H. Hall, J. Bardeen, and G. Pearson, Phys. Rev. 84, 129 (1951).
 - ² M. E. Sikorski, Physical Acoustics, Vol. 1, Part B, Edited by W. P. Mason (Academic Press, New York, 1964), Cha. 12.
 - ³ W. Rindner, J. Appl. Phys. 36, 2513 (1965).
 - ⁴ T. Imai, M. Uchida, H. Sato, and A. Kobayashi, Japanese J. Appl. Phys., 4, 102 (1965).
 - ⁵ Y. Matukura, Japanese J. Appl. Phys. 3, 256 (1964).
 - ⁶ J. J. Wortman, J. R. Hauser and R. M. Burger, J. Appl. Phys. 35, 1222 (1964).
 - ⁷ W. Rindner, Appl. Phys. Letters 6, 225 (1965).
 - ⁸ A. Goetzberger and R. H. Finch, J. Appl. Phys. 35, 1851 (1964).
 - ⁹ W. Shockley, Solid State Electronics 2, 35 (1961).
 - ¹⁰ C. A. Lee, R. A. Logan, J. J. Kleimack, and W. Wiegmann, Phys. Rev. 134, A761 (1964).
 - ¹¹ A. G. Chynoweth and K. G. McKay, Phys. Rev. 168, 29 (1957).
 - ¹² J. R. Hauser, J. Appl. Phys. 37, 507 (1966).
 - ¹³ E. O. Kane, J. Phys. Chem. Solids, 1, 82 (1956).
 - ¹⁴ W. Shockley, Bell System Techn. J. 30, 990 (1951).
 - ¹⁵ W. Shockley, Bell System Techn. J. 28, 435 (1949).
 - ¹⁶ J. Hensel, H. Hasegawa and M. Nakayama, Phys. Rev. 138, A225 (1965).

Footnotes and References (continued)

- 17 C. Herring, Bell System Tech. J. 34, 237 (1955).
- 18 H. Hasegawa, Phys. Rev. 129, 1029 (1963).
- 19 S. L. Miller, Phys. Rev. 99, 1234 (1955).
- 20 W. Paul and D. M. Warschauer, Solids Under Pressure (McGraw-Hill
Book Company, Inc., New York), 1963, Chap. 8.
- 21 M. I. Nathan and W. Paul, Phys. Rev. 128, 38 (1962).
- 22 C. Herring and E. Vogt, Phys. Rev. 101, 944 (1956).
- 23 L. Kleinman, Phys. Rev. 128, 2614 (1962).
- 24 L. Kleinman, Phys. Rev. 130, 2283 (1963).
- 25 I. Goroff and L. Kleinman, Phys. Rev. 132, 1080 (1963).
- 26 W. H. Kleiner and L. M. Roth, Phys. Rev. Letters 2, 334 (1959).
- 27 J. J. Wortman, Ph.D. Dissertation, Duke University, (1965).

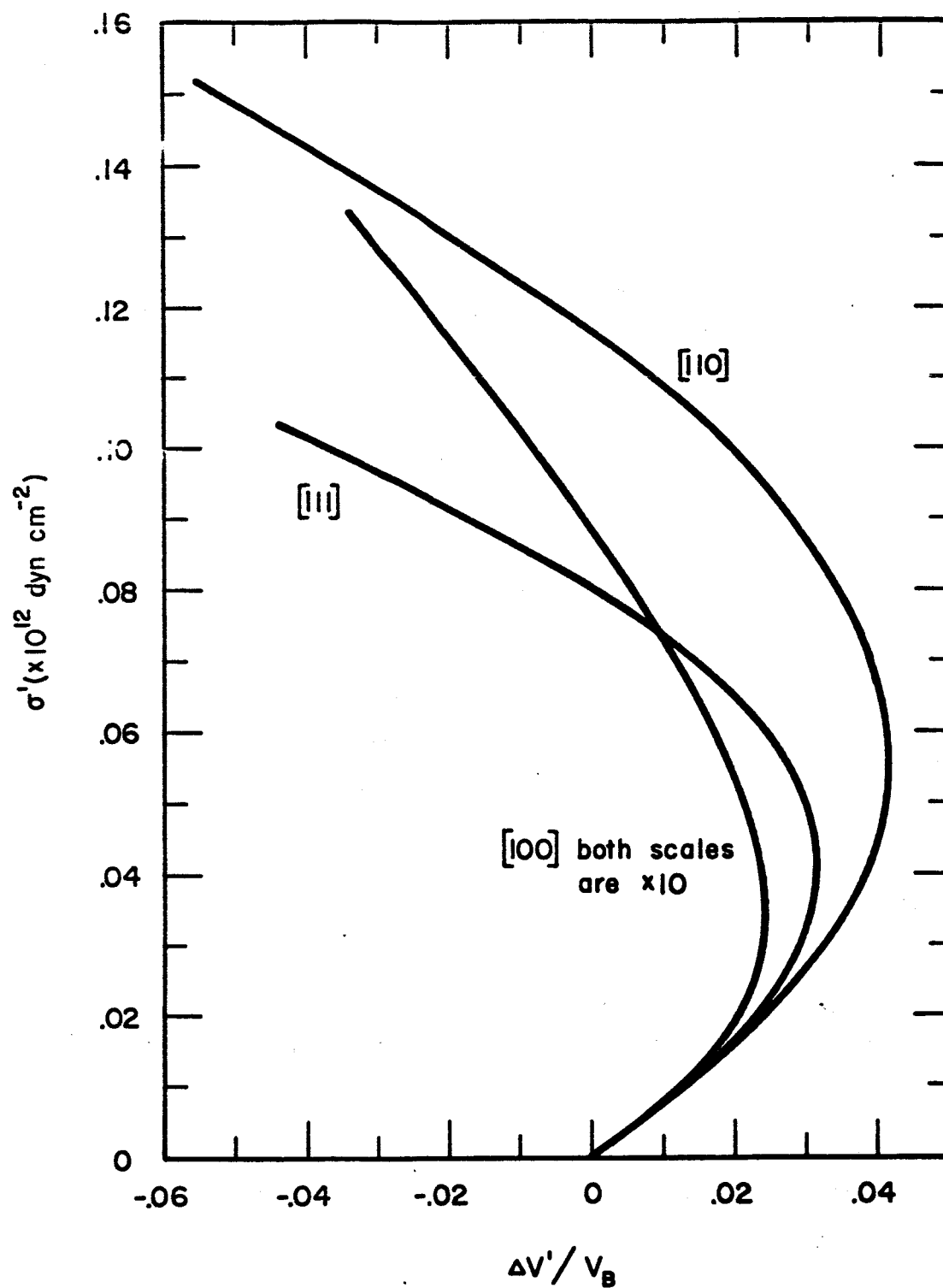


Figure 1. Theoretical values of $\Delta V'/V_B$ as a function of σ' for electrons with stress in the [100], [011], [111] directions in germanium.

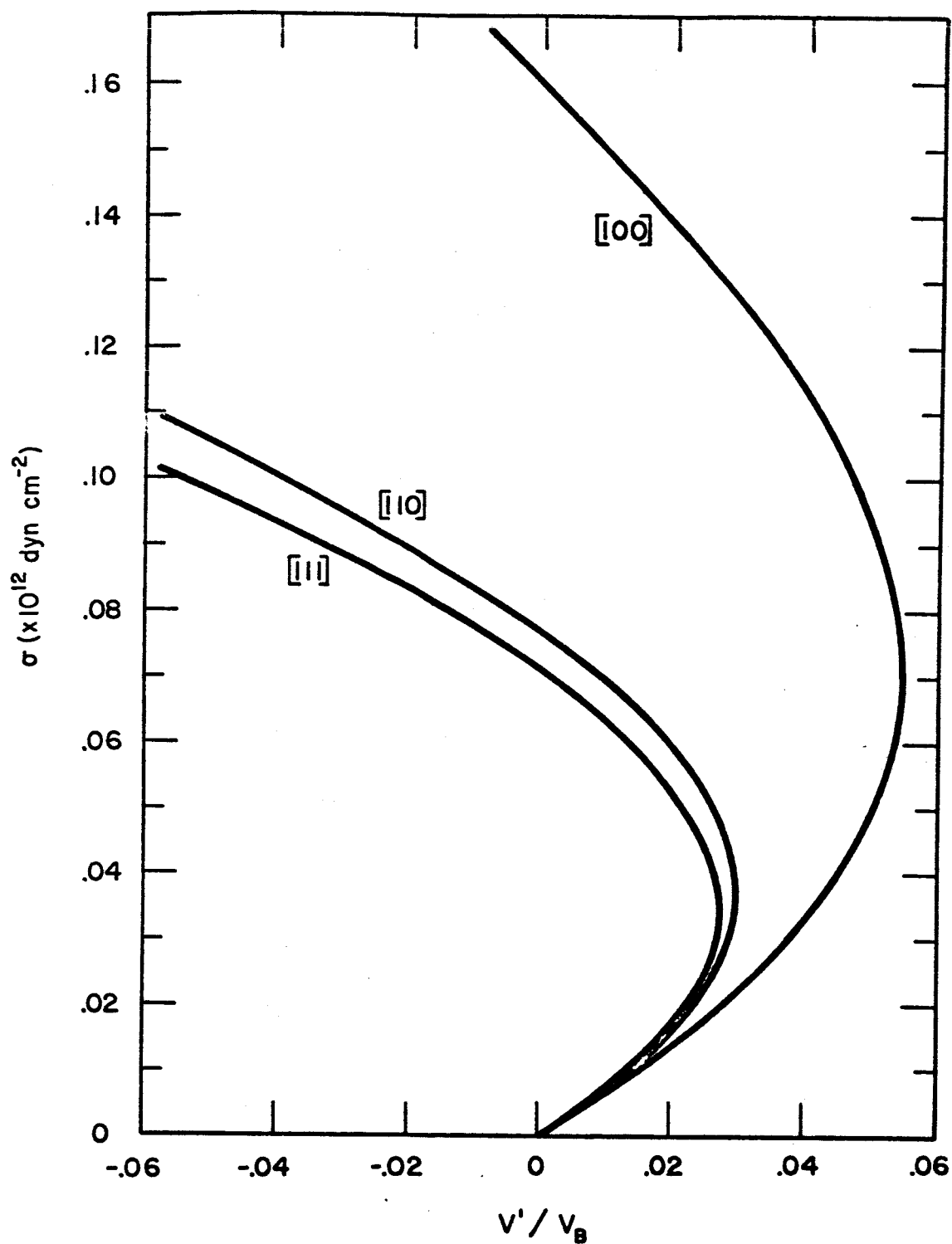


Figure 2. Theoretical values of $\Delta V'/V_B$ as a function of σ' for holes with stress in the [100], [011], [111] directions in germanium.

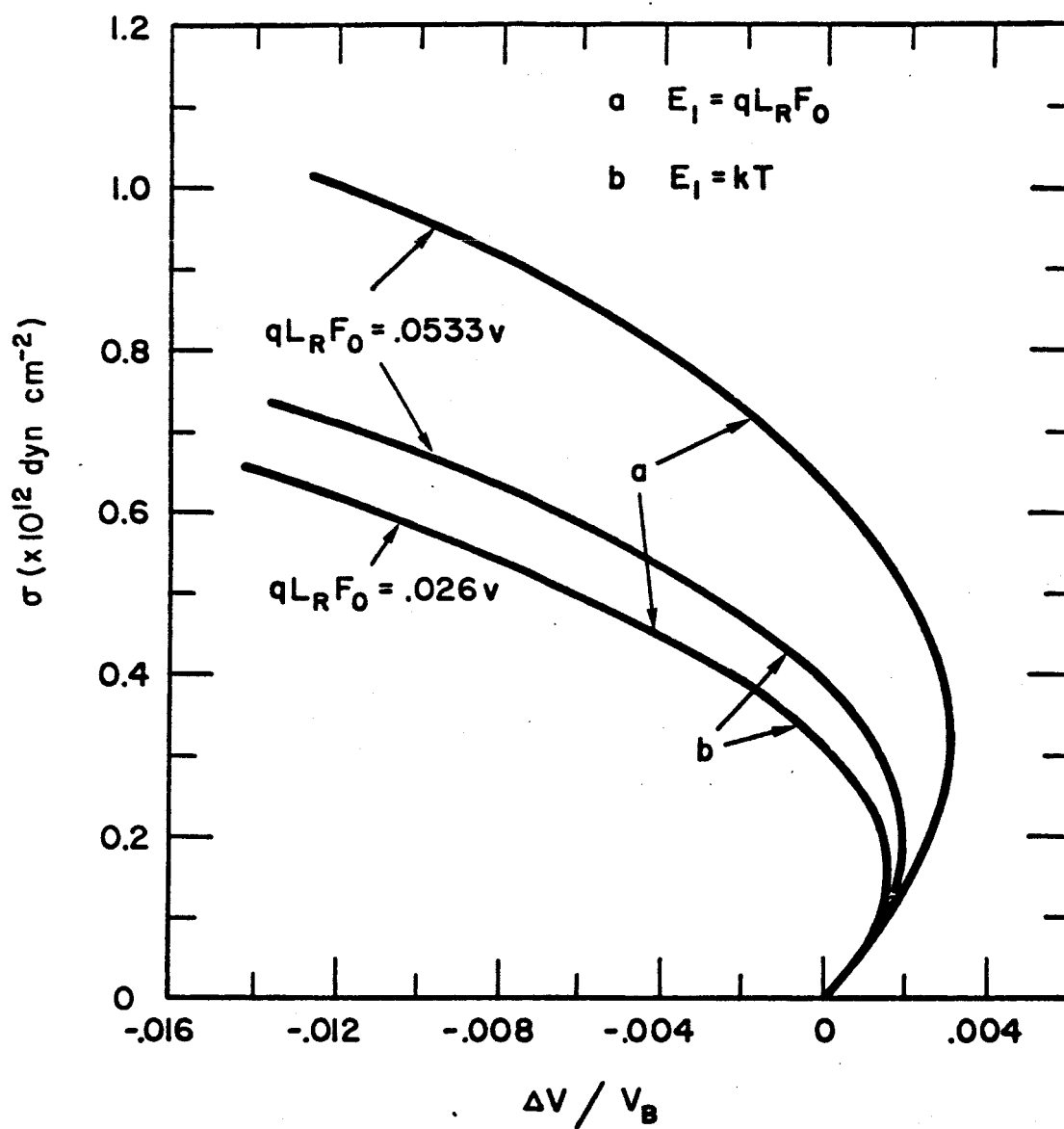


Figure 3. Comparison of electron breakdown in germanium for two values of E_1 (stress in [111] direction).

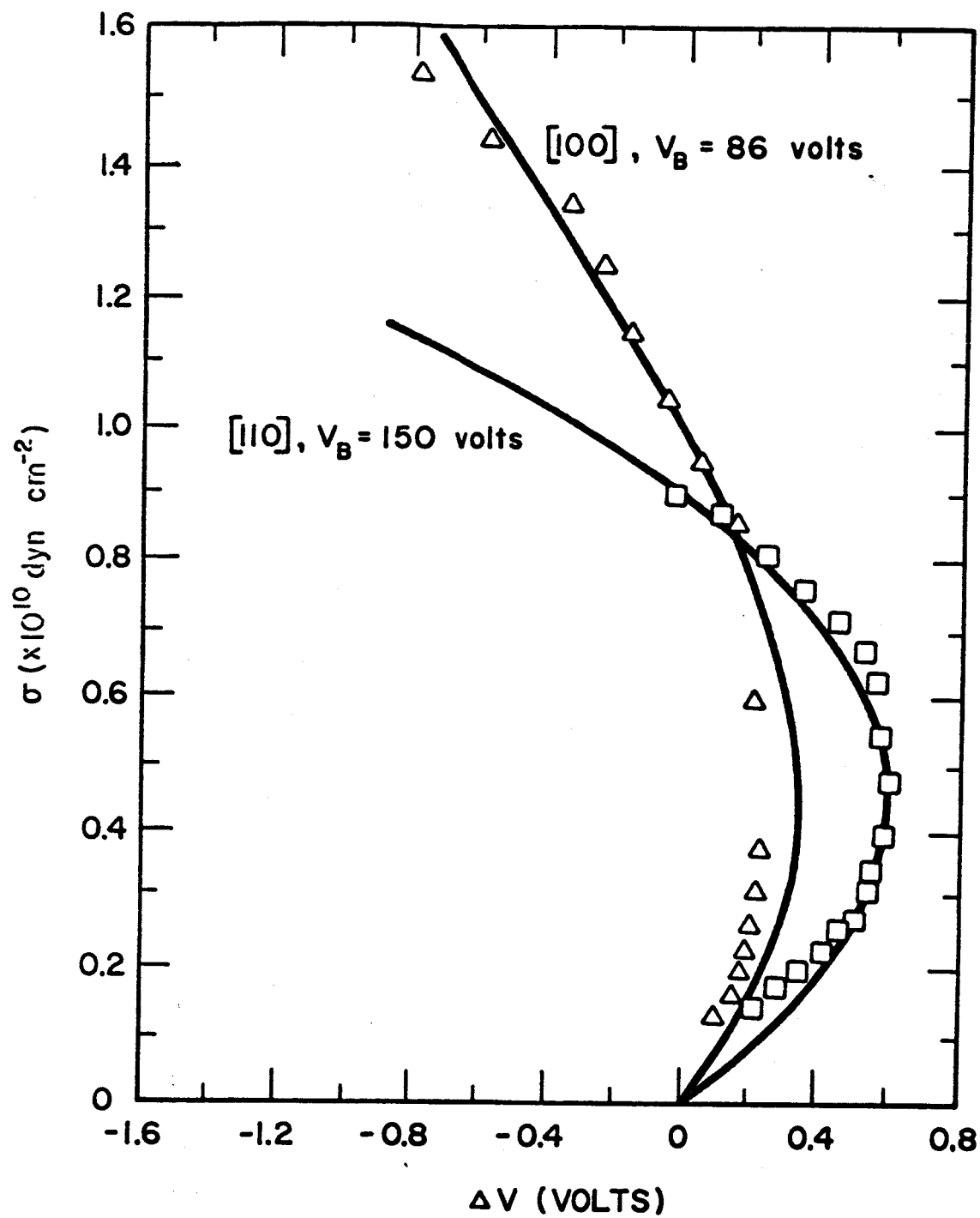


Figure 4. Change in breakdown voltage as a function of stress in germanium diodes. The solid lines are calculated values and the data points are experimental values reported by Rindner.⁷